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THE CONTROL OF PARTICULATE EMISSIONS
DURING PRODUCTION OF COKE.

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ABSTRACT

THE CONTROL OF PARTICULATE EMISSIONS DURING PRODUCTION OF COKE.

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This work is divided into two main parts, investigational and theoretical.

The first part deals with the investigation of deposition values around integrated iron and steel works, and coke works, in South Wales, and with the changes in such values which arise as a result of modifications to process control or to arrestment equipment. A method of evaluation of such changes, based on the cumulative sum technique, is developed, which minimises the effect of seasonal variations in the deposition values. It is demonstrated that there are two significant sources of particulate emission, from coke oven discharges, and from coke quenching. These are shown to have different spatial distributions, emissions from quench towers being very widespread, whereas emissions from oven discharges deposit relatively closer to the source. Methods to reduce both of these sources are described. It is shown that the use of arrestors in quench towers leads to enhanced emission of dissolved solids, but that the increase can be controlled by the use of additional sprays above the arrestors.

The second part considers some theoretical aspects of quench tower operation. It is shown that the installation of arrestors leads to changes in gas temperature and gas composition in a quench tower, which cause increases in terminal settling velocity. The same changes lead to reduced condensation within the quench tower, and hence greater emission of steam, which gives a more bouyant emission, with more widespread dispersion than from open quench towers, as well as enhanced emissions of dissolved solids. Calculations are included which confirm the extent of the dispersion from towers fitted with arrestment devices.

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DECLARATION

I hereby declare that the work embodied in this thesis is the result of my own independent investigations unless otherwise stated.

I also declare that this thesis has not been, nor is being concurrently submitted, in part or in whole, for any other degree.

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CHAPTER 1

INTRODUCTION

1.1 THE AIM OF THE INVESTIGATION

The aim of the investigation is to alleviate the major nuisance that can occur around integrated iron and steel works arising from the production of blast furnace coke. Data published by Warren Spring Laboratory indicate that emissions of dust and grit exceeding 100-200 Mg per month have been common in the U.K. from such works (18).

Material deposited over the surrounding area, as noted during investigation of complaints, and by microscopic examination of resultant samples, contains significant amounts of uncarbonised coal, and coke fines. It is not practicable to determine the specific source of these deposits, whether from oven discharge, coke quenching, or some other source, by simple physical examination. As a result, little information was available at the start of this study, on the relative significance of the two major sources, or on the spatial distribution of the emissions.

Measuring actual emissions from discharges and quenching is prone to significant errors due to the difficulties of representative sampling, and the transient nature of the operations. A method to evaluate the effect of any changes made is thus required which is based on readily available data, such as that derived from external deposit gauges.

1.2 THE PLAN OF WORK

Chapter 1 sets out the aim of the investigation, how the work has been planned for presentation in this thesis, and gives the relevant points of the legislative requirements on air pollution control in the U.K.

Chapter 2 deals with the development of a suitable evaluation method for deposition values, based on a variation of the Cumulative Sum technique, which minimises the effect of seasonal variations, and which allows the significance of changes to be determined.

Chapter 3 deals with certain modifications to grit arrestment systems at a number of coke works, and the evaluation of their effect on external deposition values for undissolved solids, using the technique developed in Chapter 2. This has shown that emissions from quench towers can be dispersed several kilometres from the source. The effect of such modifications on the deposition of dissolved solids (soluble salts) is shown to be contrary to much published assumptions.

Chapter 4 deals with the development of an improved method of carbonisation control at coke ovens, and its effect on external deposition values for undissolved solids. This has shown that dispersion of emissions during oven discharges is much less widespread than from quench towers.

Chapter 5 examines the factors affecting elutriation of particulate matter from quench towers. It is shown how the installation of grit arrestors affects the gaseous conditions within a quench tower, which then has an effect on terminal settling velocity in a manner which is beneficial in that it reduces emissions of grit and dust.

Chapter 6 examines the factors affecting the rate of steam emission from a quench tower. It is shown that the installation of arrestors, by reducing the ingress of air from the chimney effect, will also reduce condensation of steam within the tower, leading to enhanced emission of water vapour for a given rate of quenching. The effect of this on enhancing the dispersion of dissolved solids from the quench water is demonstrated.

Chapter 7 examines the effect of the changes in exit gas composition, temperature, and emission rate on the rise of the bouyant plume from the quench tower, and dispersion of the solids carried in the plume. It is shown that the installation of arrestors leads to greater dispersion.

Chapter 2-7 each carry their own conclusions. These are all to be found together after Chapter 7.

The S.I. units used throughout this work have been based on the recommendations of BS 5555:1981 (44).

1.3 AIR POLLUTION CONTROL AT SCHEDULED PREMISES

The legislation which applies in England and Wales to the control of air pollution from scheduled premises consists of the Alkali Etc. Works Regulation Act 1906 (1), together with parts of the Health and Safety at Work Act 1974 (33), and the Health and Safety (Emissions into the Atmosphere) Regulations 1983 (49). These are enforced by H.M. Industrial Air Pollution Inspectorate (HMIAP I).

The basic U.K. approach remains the use of "Best Practicable Means", as defined in section 5 of the above 1974 Act:

"It shall be the duty of the person having control of any premises of a class prescribed for the purpose.... to use the best practicable means for preventing the emission into the atmosphere from the premises of noxious or offensive substances, and for rendering harmless and inoffensive such substances as may be so emitted."

Notes on Best Practicable Means have been published for Coke Works (38). The word "practicable" has been defined in other legislation (6) as follows:-

"Practicable" means reasonably practicable having regard, amongst other things, to local conditions and circumstances, to the financial implications, and to the current state of technical knowledge.

In the case of the operations considered in this study, "Best Practicable Means" concentrates on correct process control, and on the use of arrestment equipment to minimise emissions from quenching.

1.4 AIR POLLUTION CONTROL AT COKE WORKS

The detailed requirements for air pollution control at coke works have been published (38). The relevant parts are:-

CARBONISING

Every effort should be made to operate to a regular carbonising cycle. Undercarbonised ovens shall not be deliberately discharged except in an emergency. Abnormal conditions causing excessive emissions on oven discharging shall be notified at the onset to the Inspectorate. Normal carbonising times and temperatures shall be notified to the Inspectorate and records kept for examination.

COKE QUENCHING

All wet coke quenching or dry coke quenching systems shall be fitted with grit arrestment to the satisfaction of the District Inspector.

Blast furnace coke is required to be reactive, and is produced using high heating flue temperatures, with carbonisation periods of circa 18h for ovens of 450mm width. There is a desire on the part of the coke producer to avoid over-carbonisation, and this can on occasions lead to unacceptable emissions during oven discharge. The extent of these can be seen in the photographs in Chapter 4, and on a major works there may be one such discharge every 20min. or less.

Following the discharge of the coke, the product is transferred to a quench tower, where it is quenched with large volumes of water (450-500kg Mg⁻¹ of coke). On a calm day, the steam plume may rise above 500m. By contrast, in high winds the plume may be pulled down to ground level within 200m of the tower.

CHAPTER 2

DEVELOPMENT OF THE DEPOSITION CUSUM

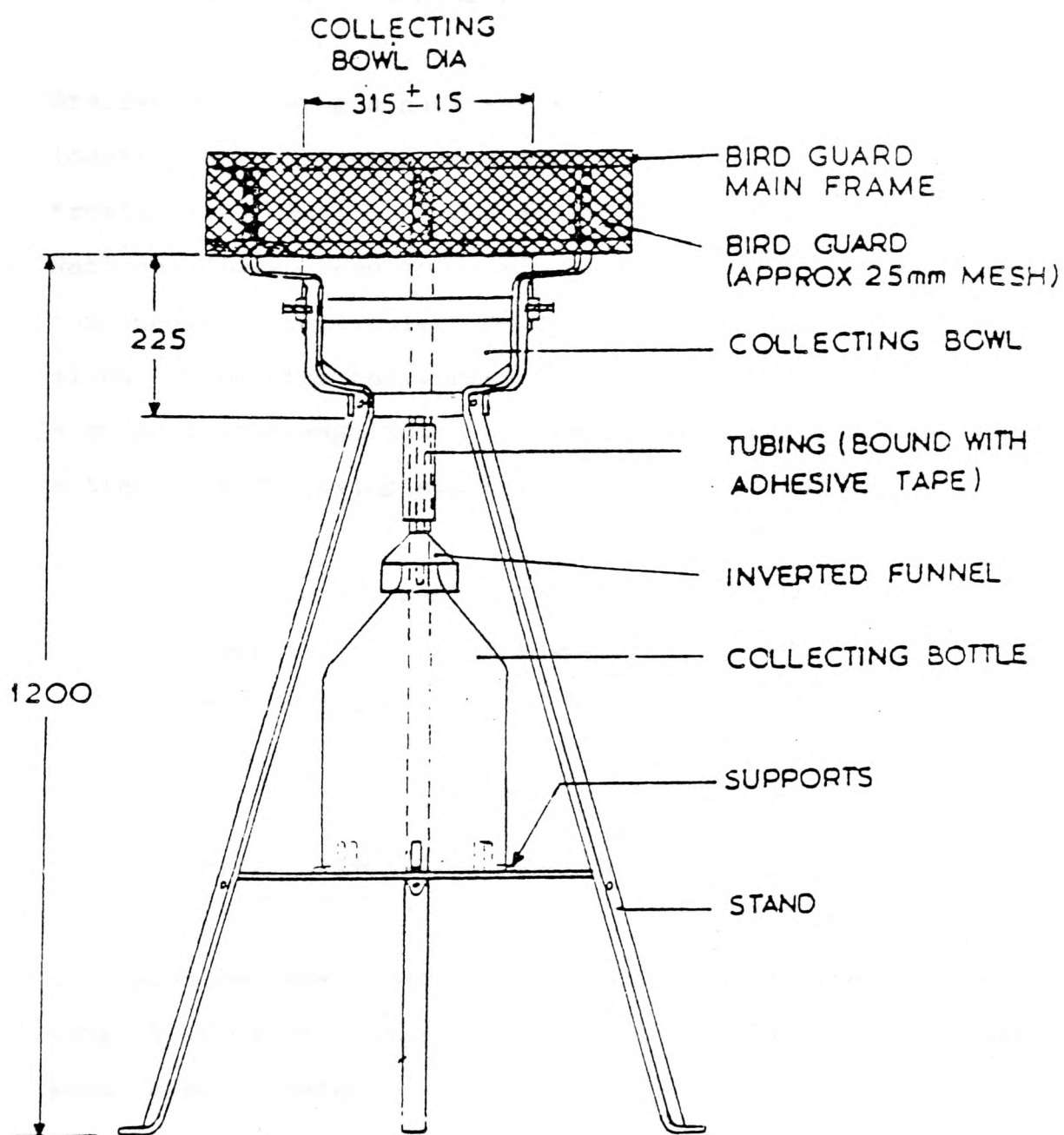
2.1 DEPOSITION DATA IN THE U.K.

Deposition data have been published by Warren Spring Laboratory (W.S.L.) for a number of years as part of the National Survey (18). The results are published annually, and consist of monthly averages for specific sites. The sites are usually operated by Local Authorities, and in general they fall into one of two categories:-

- (a) To provide background information for the district,
- (b) To monitor a specific emission source.

The deposited matter is collected in British Standard Deposit Gauges (see Fig.1). The material collected may be analysed for a number of parameters, of which the most usual are: quantity of rainfall, pH of collected liquor, dissolved solids content, undissolved solids, and residue after combustion. National Survey sites are classified into 13 types of location. The majority of those used in this study are classified as being "in open country to monitor a particular source." (Site code 12).

The main part of this study is concerned with deposition around B.S.C. Llanwern, which is monitored by 7 B.S. gauges operated by Newport B.C. (35). Much of the data has been published already by W.S.L. Results were supplied to the Inspectorate monthly by Newport B.C., and are expressed in $\text{mg m}^{-2} \text{ day}$. The present study considers data from January



all dimensions in mm

FIG.1 BRITISH STANDARD 1747 PART 1, HORIZONTAL DUST DEPOSIT GAUGE

1976 onwards, since it was in 1976 that the major expansion took place on the Llanwern site. Collection of deposition data was suspended by Newport B.C. in October 1984.

Statistics showing annual averages for certain types of location are published from time to time, but these must be treated with caution. The averages are usually based on National Survey results, and these are only the averages obtained from particular gauges, most of which have been sited to monitor industrial emissions. However, purely as a guide to the magnitude of deposition values, one can extract the following approximate annual averages:

Open country, general deposits	50
Commercial centre of town	100
Purely industrial area	150

Table 1.

TYPICAL DEPOSITION VALUES(mg m^{-2} day)

In practice, the annual averages for such sites may vary from 50-200% of these values, and individual months may show even greater variations. Moreover, there is an underlying slow trend to lower values as the drive for clean air continues throughout the country.

2.2 PRESENTATION OF THE RAW DATA

The problem of evaluation of deposition values can be seen from the bar charts in Figs. 3(a)-(g), which show the raw data from January 1976 until July 1984, the graphs being arranged in order of increasing distance of the gauges from the sources, the nearest being 750m away, and the furthest 4200m. The locations of the gauges are shown in Fig.2.

The results from each gauge cover a wide range of values in each year, caused by variations in such things as:-

- (a) Production rates at the iron and steel works,
- (b) Control of process emissions,
- (c) Seasonal variations, especially in wind speed and wind direction,
- (d) Changes in emissions external to the iron and steel works.

It can be seen from the charts that, although deposition values in earlier years had been unacceptably high, the values from 1983 onwards indicate that an acceptable level of control of particulate emissions had been achieved.

During the period of the study, two specific sets of changes were introduced in the coke production area:-

- (i) Repairs and modifications to grit arrestors during September 1980,
- (ii) Carbonisation control on the 4m batteries from November 1981, and on the 6m battery from July 1982.

An evaluation method is needed to estimate the contribution of each change towards the overall improvement.

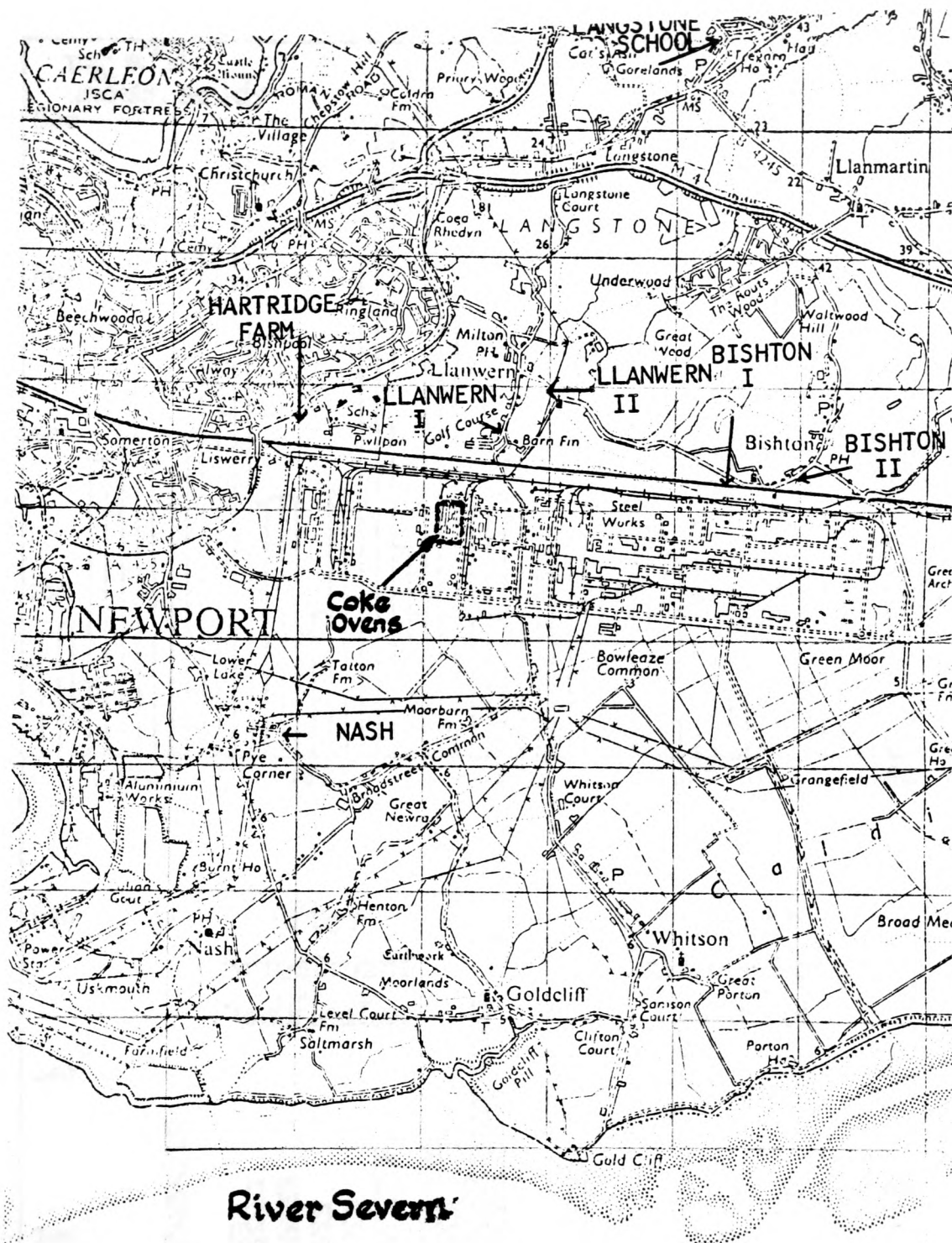


Fig. 2
Newport Borough Council
Environmental Health Department
Gauge Locations

Fig. 3c Deposition Data - Hartridge

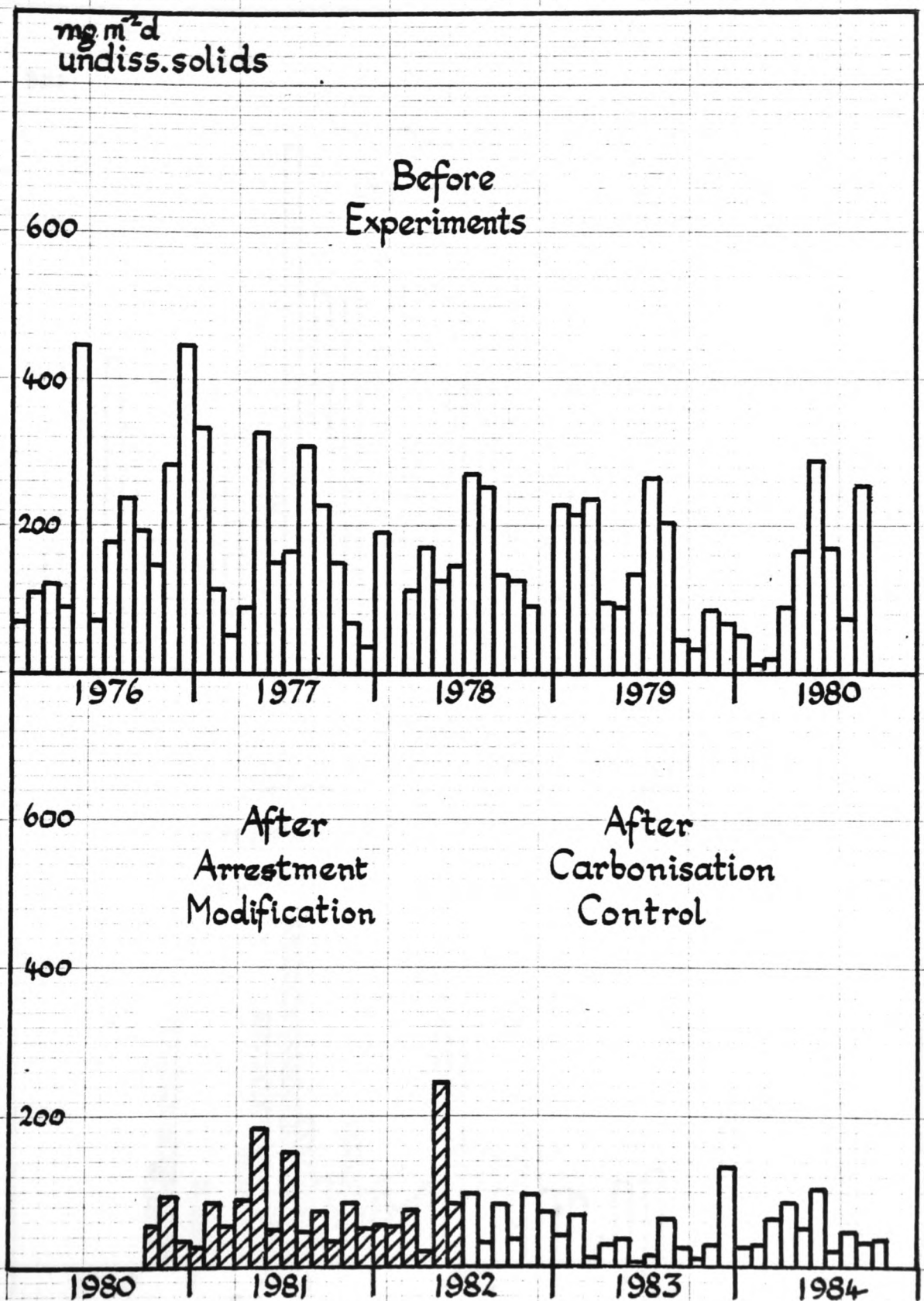


Fig. 3d Deposition Data - Nash

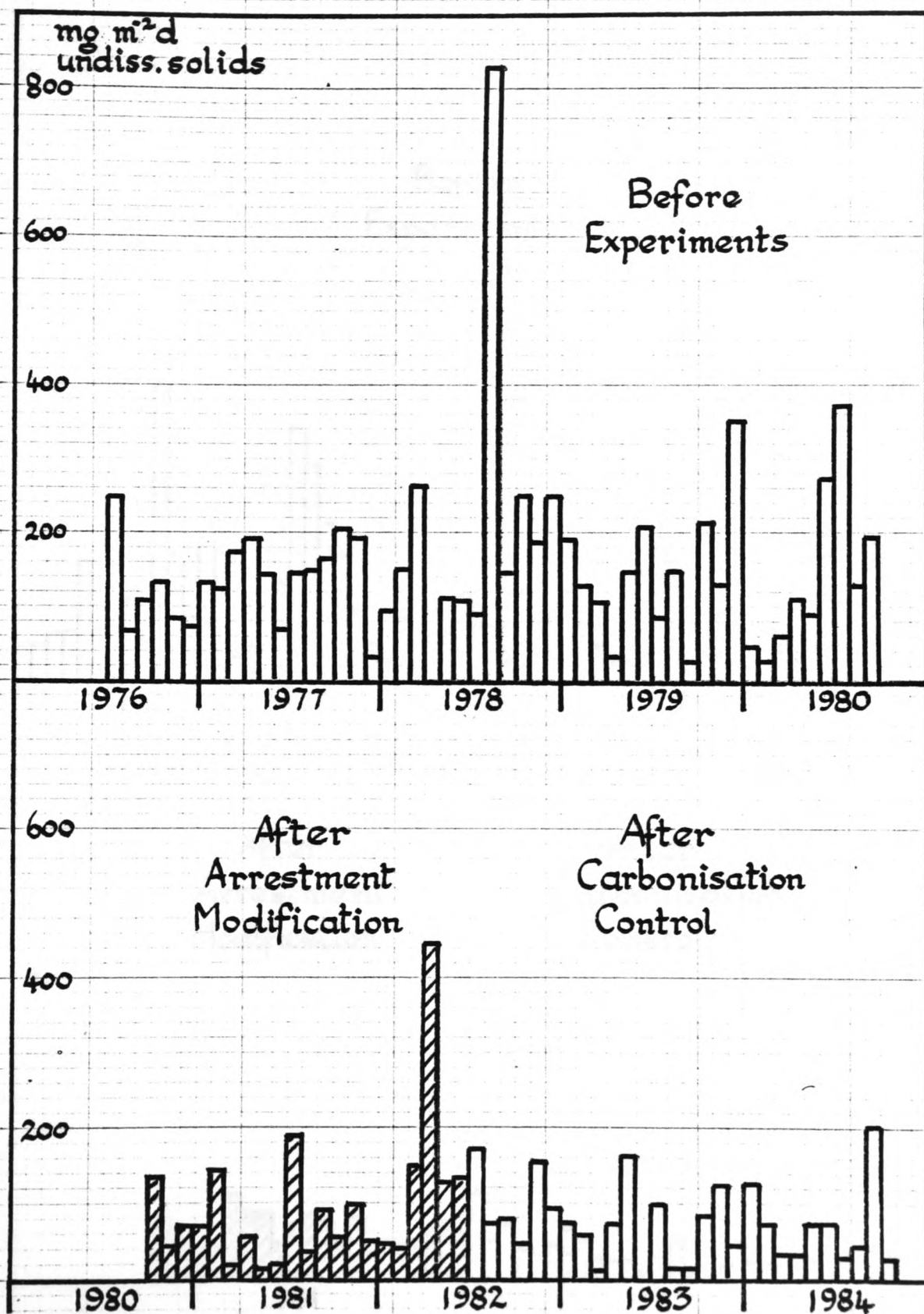


Fig. 3f Deposition Data – Bishton 2

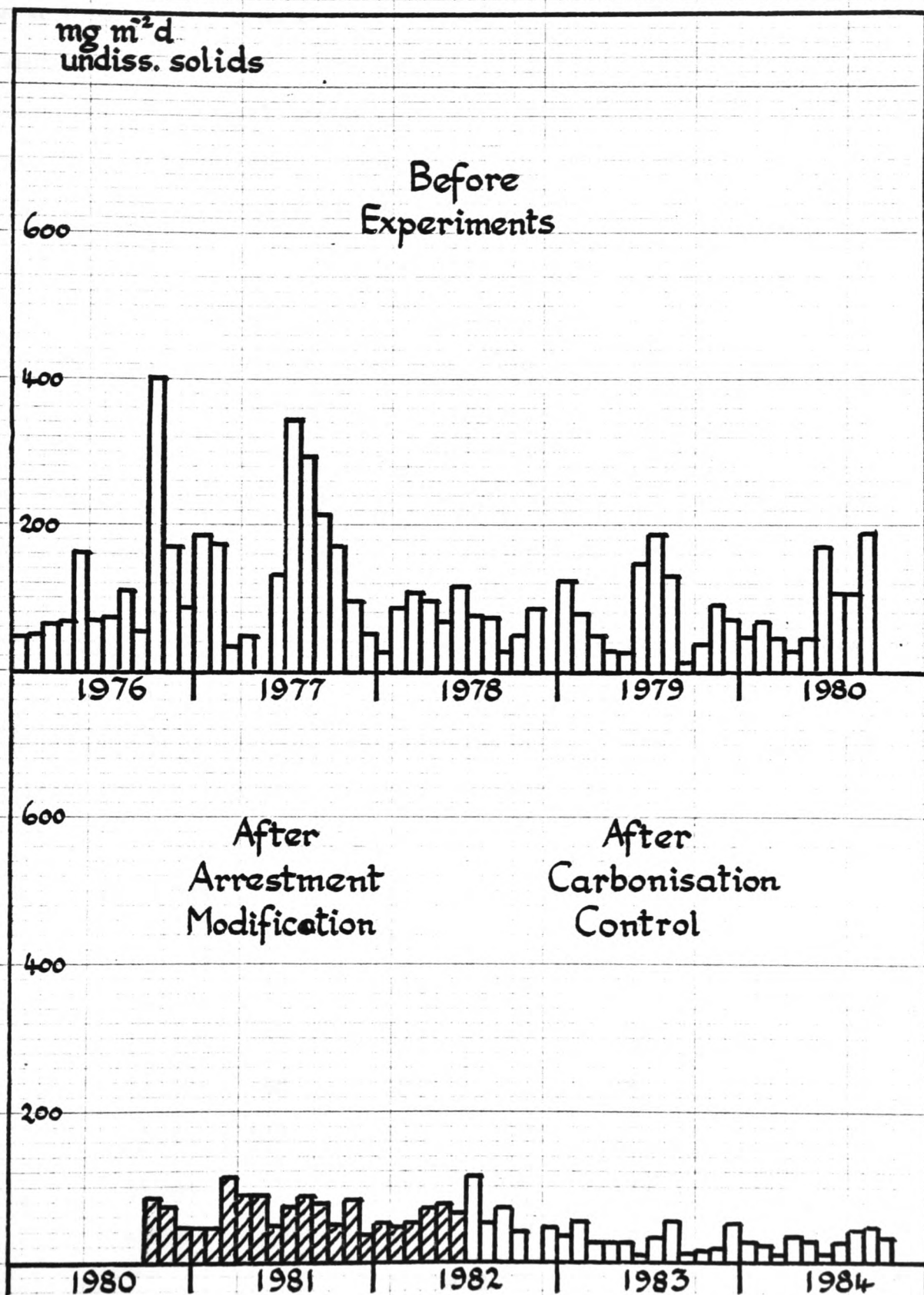


Fig. 3g Deposition Data - Langstone

2.3 BACKGROUND DEPOSITION VALUES IN THE LLANWERN AREA

A unique opportunity to estimate background deposition values arose when there was a prolonged strike in a major part of the steel industry in the first quarter of 1980. At B.S.C. Llanwern, production of steel ceased, but the coke ovens were maintained in operation, albeit at a very low level. Carbonisation periods were 200-300% of normal at reduced heating flue temperatures. During this period, deposition values were much lower than usual. Except for the two nearest gauges, the quarterly average results were close to the averages given in Table 1 for general deposits in open country. The two nearest gauges collected less than would be expected in the commercial centre of a town.

The results are compared with the corresponding averages for earlier years in Table 2. This shows that under normal operating conditions, the environmental impact of the works had been considerable during that period.

Distance	1976	1977	1978	1979	1980
700m	139	494	410	223	84
1300m	126	414	407	241	75
1500m	66	214	97	80	55
2200m	99	167	152	225	28
2200m	135	285	194	173	66
2800m	-	115	170	141	42
4200m	54	130	73	84	53

Table 2.

AVERAGE DEPOSITION VALUES JAN.-MARCH ($\text{mg m}^{-2} \text{ day}$)

2.4 THE CUMULATIVE SUM TECHNIQUE

Cumulative Sum (CuSum) techniques are a comparatively recent development. Experience in several fields has shown that they are a valuable aid in decision-making and evaluation. The techniques used in this study are based on a publication by Woodward and Goldsmith (21). Techniques based on CuSums can be used for:-

- (a) Detecting changes in the average value of the data.
- (b) Determining the time of onset of such changes.
- (c) Obtaining a reliable estimate of the current average value.
- (d) Predicting future average levels in the short-term.

CuSum techniques have provided important advances in the speed with which changes from the average value can be detected.

2.5 CALCULATION OF CUMULATIVE SUMS

Suppose we have a set of results, which we will denote by x_1, x_2, \dots , derived in that order at equal intervals of time. From the first result, a quantity k is subtracted. This simple calculation changes the origin of the measurement to a position called the "reference value", k . The difference $(x_1 - k)$ for the second result is then calculated and added to the first difference. Subsequent differences are added to those already accumulated, thus building up the following series:-

$$S_1 = (x_1 - k)$$

$$S_2 = (x_1 - k) + (x_2 - k) = S_1 + (x_2 - k)$$

$$S_3 = S_2 + (x_3 - k)$$

.....

$$S_n = S_{n-1} + (x_n - k) = x_1 + x_2 + x_3 + \dots + x_n - n.k$$

These simple functions of the observed results are known as the CuSums. They are generally plotted as a time-series as each observed value is incorporated, the ensuing graph being known as a "cumulative sum chart". An example calculation is shown in Table 3 for 40 data values, with a mean of 10, and much scatter, the values ranging from 2 to 16. The mean value of 10 will be taken as the reference value. The plots of the data values and the cumulative sum of the differences give rise to Figs. 4 and 5 respectively.

DATA VALUE	DIFFERENCE FROM REFERENCE VALUE	CUMULATIVE SUM OF DIFFERENCES
9	- 1	- 1
16	+ 6	+ 5
11	+ 1	+ 6
12	+ 2	+ 8
16	+ 6	+ 14
7	- 3	+ 11
13	+ 3	+ 14
12	+ 2	+ 16
13	+ 3	+ 19
11	+ 1	+ 20
12	+ 2	+ 22
8	- 2	+ 20
8	- 2	+ 18
11	+ 1	+ 19
14	+ 4	+ 23
8	- 2	+ 21
8	- 2	+ 19
14	+ 4	+ 23
4	- 6	+ 17
13	+ 3	+ 20
12	+ 2	+ 22
8	- 2	+ 20
8	- 2	+ 18
12	+ 2	+ 20
6	- 4	+ 16
14	+ 4	+ 20
13	+ 3	+ 23
3	- 7	+ 16
9	- 1	+ 15
7	- 3	+ 12
14	+ 4	+ 16
2	- 8	+ 8
6	- 4	+ 4
4	- 6	- 2
8	- 2	- 4
13	+ 3	- 1
10	0	- 1
13	+ 3	+ 2
8	- 2	0
12	+ 2	+ 2

TABLE 3

A SPECIMEN CUSUM CALCULATION

The plots of the data values and the cumulative sum of the differences give rise to Figs. 4 & 5 respectively.

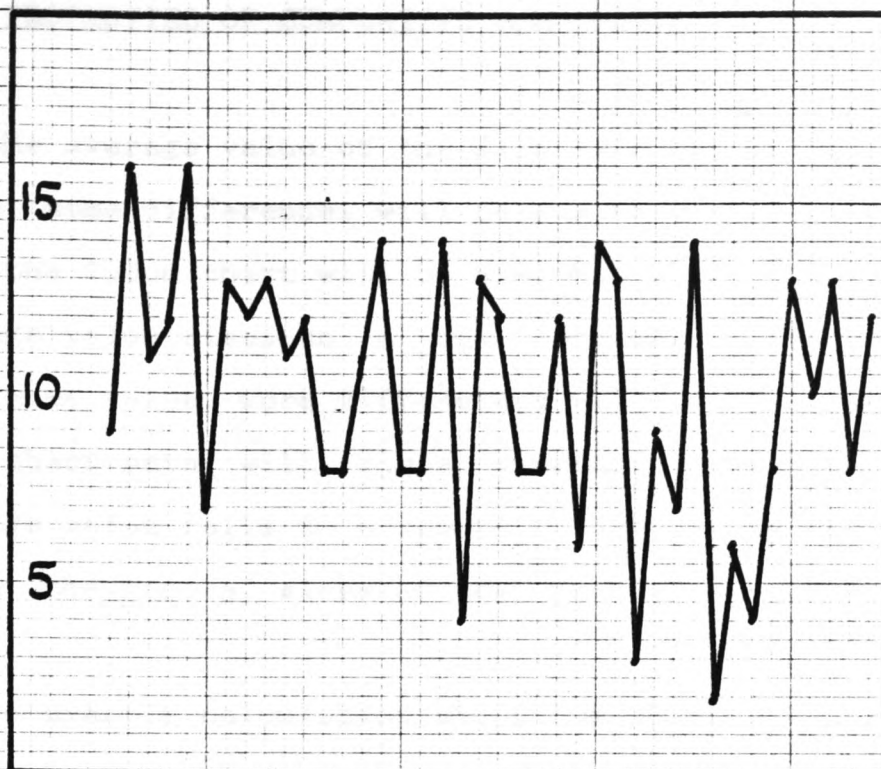


Fig. 4

A plot of typical data values



Fig. 5

An Example Of A Cumulative Sum Chart

2.6 PROPERTIES OF CUMULATIVE SUM CHARTS

If the average value of the data is close to the reference value, some differences will be positive and some negative, and the CuSum chart will be essentially horizontal. If the average value rises to a new constant level above the reference value, more differences will be positive, and the mean chart path will slope upwards. Likewise, if the average value falls to a constant level below the reference value, the general slope of the chart will be downwards.

In the example calculation and CuSum chart given in section 2.5, three distinct portions of the chart can be seen with clear changes of slope between each portion. In the first, the average value is greater than the reference value, giving an upward slope; in the centre, the average is close to the reference value, giving a portion which is essentially horizontal; in the final portion, the average is below the reference value, giving a downward slope.

The further the current mean process level is away from the reference value, the steeper will be the slope of the CuSum chart. In fact, the slope of the line joining two points on the chart measures the average difference between those two points. The mean level (\bar{x}) over any portion of the CuSum chart is given by:-

$$\bar{x} = k + (\text{Change in CuSum})/(\text{Change in } n) \quad (2.6.1)$$

Some care is needed in the choice of reference value. If it is lower than all the results, then each CuSum will exceed its predecessor, the plotted points will rise continuously, and can easily run off the top of the chart. Also, changes of slope are most easily distinguishable if they are accompanied by a change of sign of the slope. The reference value is thus usually taken as a target value around which the results are expected to vary, or as the calculated mean of a set of results already to hand.

One of the main virtues of CuSum charts is that relatively small changes in mean value appear as quite clearly different slopes. However, in addition to the choice of reference values, the visual picture depends to some extent on the scales chosen for the axes of the chart.

Woodward and Goldsmith (21) recommend that, if the horizontal distance between plotted points is regarded as one unit, then the same distance on the vertical plane should be very approximately 2σ , where σ is the standard deviation (S.D.) of the short-term variability of the series. With this system of scaling, the mean path of the chart will make an angle of 45° with the horizontal when the series averages 2σ difference from the reference value and purely random variations will appear quite small. It is also generally desirable that no slope should exceed 60° , since angles greater than that are relatively insensitive to changes in the mean value of the series.

2.7 EXAMINATION OF DEPOSITION DATA BY THE CONVENTIONAL CUSUM TECHNIQUE

The results from the 7 gauges around B.S.C. Llanwern were examined by the conventional CuSum technique, using the "post mortem" method, with the raw data, and without any correction for freak results. Missing data, or results noted as contaminated, were replaced by dummy values based on the mean of the values before and after.

The grand mean of the results for each gauge was taken as the reference value, in which case the final value of the CuSum would be close to zero. By convention the origin is the first point on the chart, so there is some symmetry using this method. The points where the main modifications took place were September 1980 for the grit arrestors, and mid-1982 for carbonisation control on the 6m ovens.

In deciding the vertical scale for the charts, the residual S.D. was found using the method suggested by Woodward and Goldsmith (21), whereby a provisional estimate is given by:

$$\left\{ \sum_{i=1}^{n-1} (x_{i+1} - x_i)^2 / 2(n-1) \right\}^{0.5}$$

This formula normally reaches a steady value after about eight terms. Two values were calculated in each case; one using the terms in consecutive order, and the other using the same terms in reverse order. The provisional estimate was taken as the mean of these two values.

The residual S.D. was calculated from deposition values obtained after the main experiments had been completed. Examples of CuSum charts around B.S.C. Llanwern are shown in Figs.6 and 7, one for a distant gauge (2200m) and one for a nearby gauge (750m). (These confirm that the deposition values during the strike period were atypical).

With each of the 7 gauges, prior to the modifications, there was a marked seasonal variation, which limited the sensitivity of any evaluation, and indicated that the conventional CuSum technique may not be particularly useful for evaluation of deposition data. The magnitude of the seasonal variations can be seen to be much reduced after the two modifications.

The slopes of the CuSum charts were estimated by constructing boundary lines which encompass all values in the required section, and then drawing the mid-line. The magnitude of the improvements can then be derived from the changes in slope.

The results of this evaluation are shown in Table 4. This indicates that the two experiments led to reductions of at least 50% in the amount of deposited matter in the external gauges. (The reductions at the most distant gauge were not significant). Since the gauges also collect material from other sources, the reduction in the environmental impact from the sources under investigation will be greater than the values shown.

- a. commissioning of 6m. ovens
- b. production cut-back and prolonged strike
- c. production re-start after strike
- d. modifications to grit arrestment
- e. carbonisation control on 6m. ovens

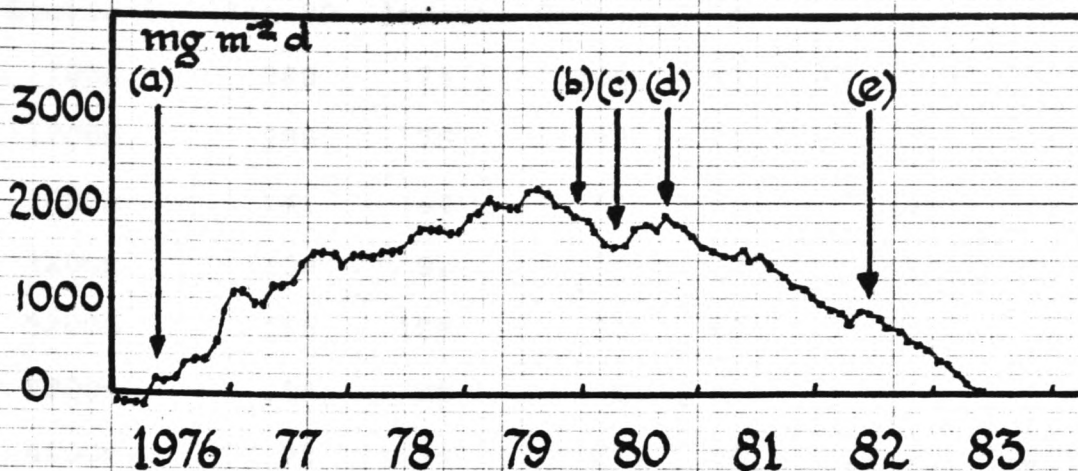


Fig. 6
Conventional CuSum Chart
Based On Deposition Data.
Distant Gauge

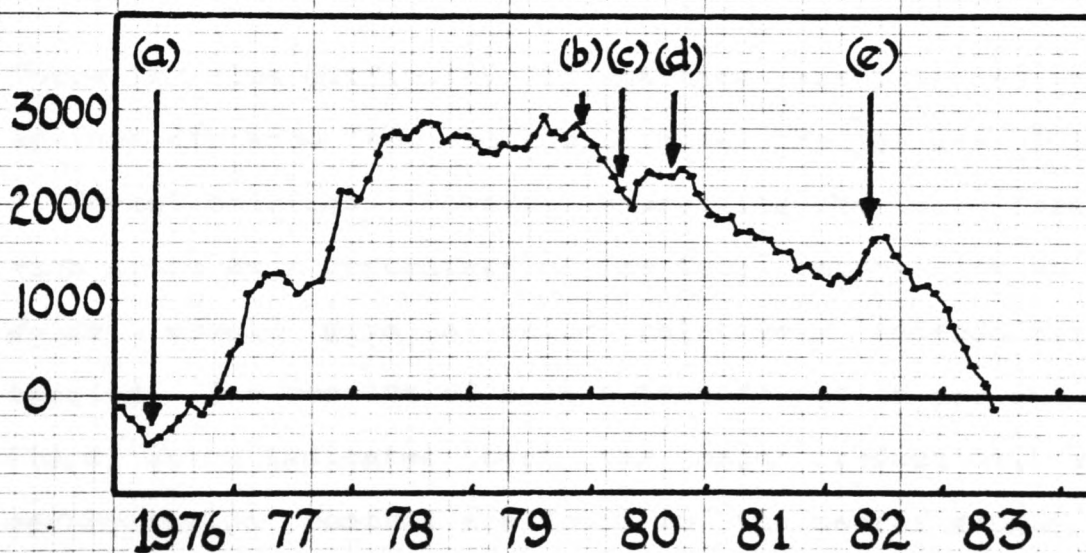


Fig. 7
Conventional CuSum Chart
Based On Deposition Data.
Nearby Gauge

Distance From Source	Mean	Reduction			%Contribution	
	Before	Grit	Carb.	Total	Grit	Carb.
	Jan.80	Arrest.	Control	%	Arrest.	Control
700m	269	75	106	67	41	59
1300m	288	73	132	71	36	64
1500m	141	44	57	72	43	57
2200m	169	92	32	73	74	26
2200m	265	126	53	66	70	30
2800m	166	98	0	59	100	0
4200m	82	14	27	50	N/S	N/S

Table 4
EVALUATION OF DEPOSITION DATA BY
CONVENTIONAL CUSUM TECHNIQUE

There is some difficulty in charting absolute reductions against distance from source, since the gauges lie at different bearings. However, expressing the improvement at each gauge as a percentage of the total improvement at that gauge should give a value relatively independent of bearing. The results of such a transformation are shown in Fig.8, which indicates that the major reductions after carbonisation control are found in the nearer gauges, and that in the more distant gauges the improvements are very modest. By contrast, the improvements following grit arrestment modifications are less in the nearer gauges, but in the more distant gauges they can be attributed almost entirely to these modifications.

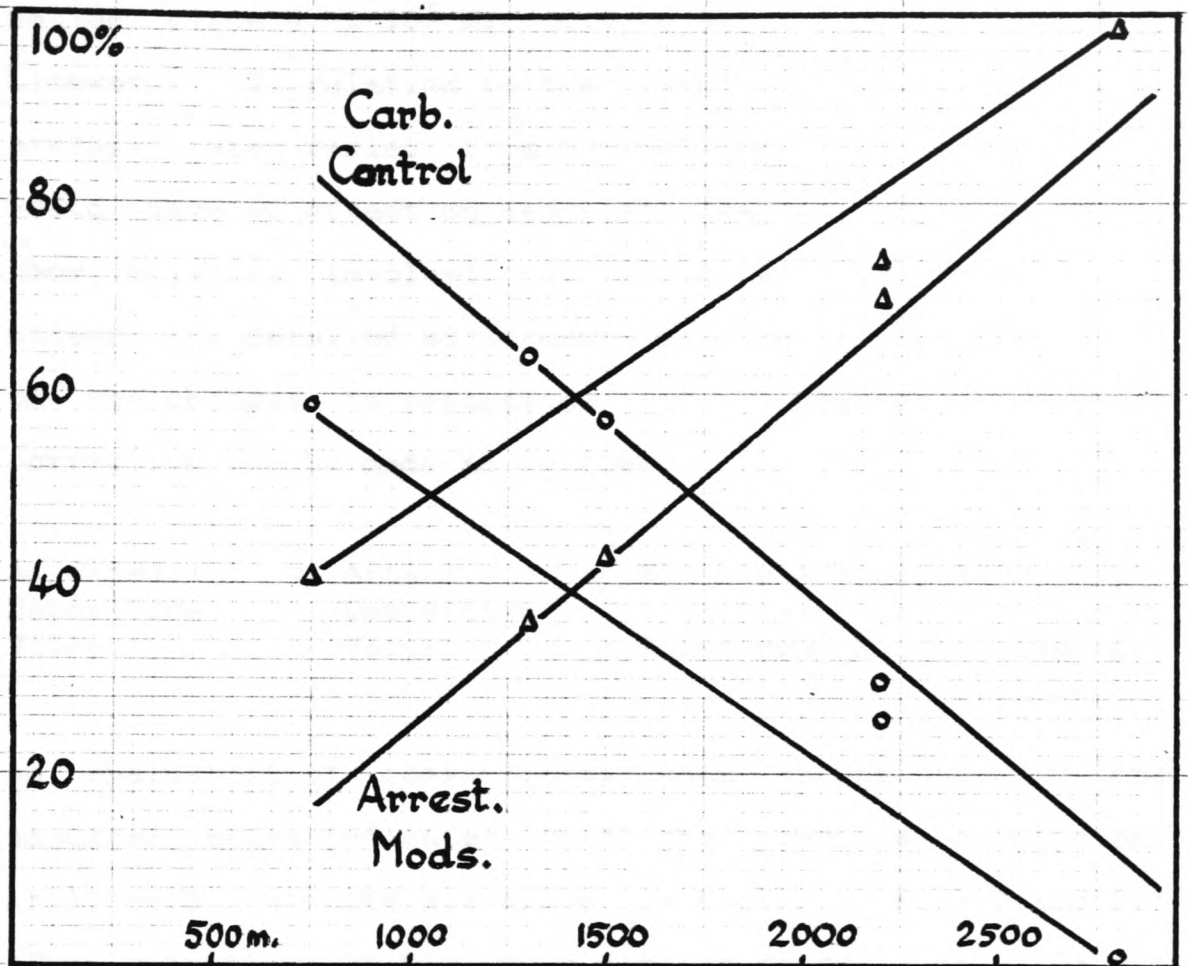


Fig. 8
Relative Contribution To Overall Improvement
Vs Distance From Source

2.8 THE EFFECT OF COKE PRODUCTION RATE

During the period covered by the conventional CuSum evaluation, circa 6×10^6 Mg of coke were produced at B.S.C. Llanwern. In relation to the grand mean production rate, average rates varied from 50-150% and this clearly would have an effect on deposition values. In view of the many variables involved, it would not be feasible to attempt any detailed adjustments to deposition values based on the changes in production rates. However, a partial correction can be made as follows:-

$$\begin{array}{lcl} \text{Adjusted} & = & \text{Actual} \quad \times \quad \text{Monthly Average Production} \\ \text{Deposition} & & \text{Deposition} \quad \frac{\text{-----}}{\text{Grand Mean Monthly Average}} \\ \text{Value} & & \text{Value} \end{array}$$

An evaluation of conventional CuSum charts based on the adjusted values indicates that the previous conclusions still hold. Results are shown in Table 5, Figs.9 and 10. (The reductions at the most distant gauge were still not significant.) Relative contributions of the two improvements versus distance from source are shown in Fig.11. This confirms that carbonisation control caused the major reductions close to the source, while grit arrestment modifications also produced reductions in more distant gauges. However, on the CuSum charts, seasonal variations remains as a cause of reduced sensitivity using this approach. Attention is therefore given in the following

sections to developing a method which minimises the seasonal effect at any gauge.

Distance From Source	Mean	Reduction			%Contribution	
	Before	Grit	Carb.	Total	Grit	Carb.
	Jan.80	Arrest.	Control	%	Arrest.	Control
700m	241	47	102	62	32	68
1300m	276	57	153	76	27	73
1500m	115	44	38	63	54	46
2200m	179	110	16	70	87	13
2200m	219	90	81	65	53	47
2800m	135	64	0	47	100	0
4200m	83	8	28	43	N/S	N/S

Table 5
EVALUATION OF DEPOSITION DATA BY
CONVENTIONAL CUSUM TECHNIQUE
AFTER ADJUSTMENT FOR COKE PRODUCTION RATE

Meanings of subscripts given in Fig.6

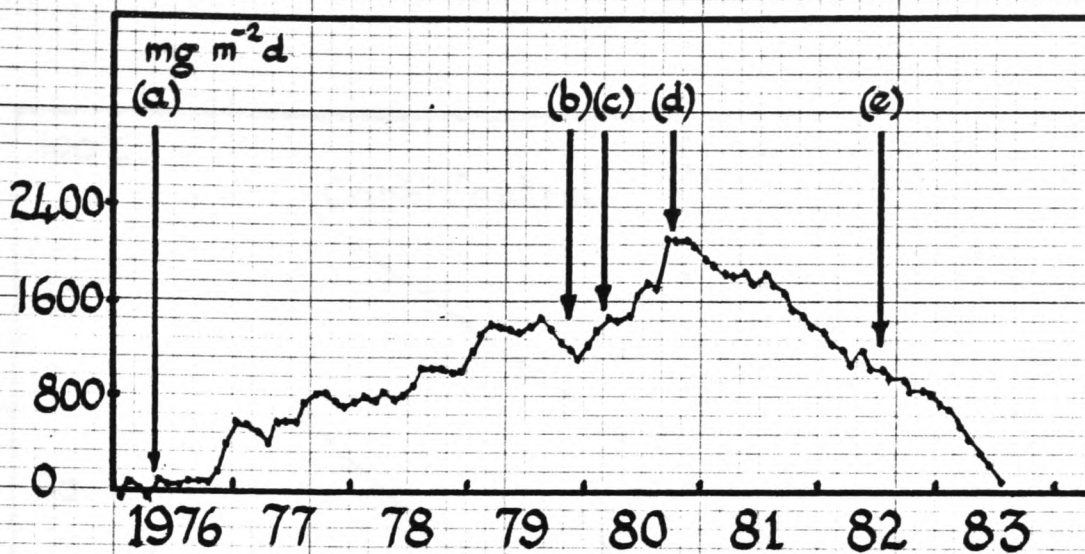


Fig.9

Conventional CuSum Chart
With Adjustment For Coke Production Rate
Distant Gauge

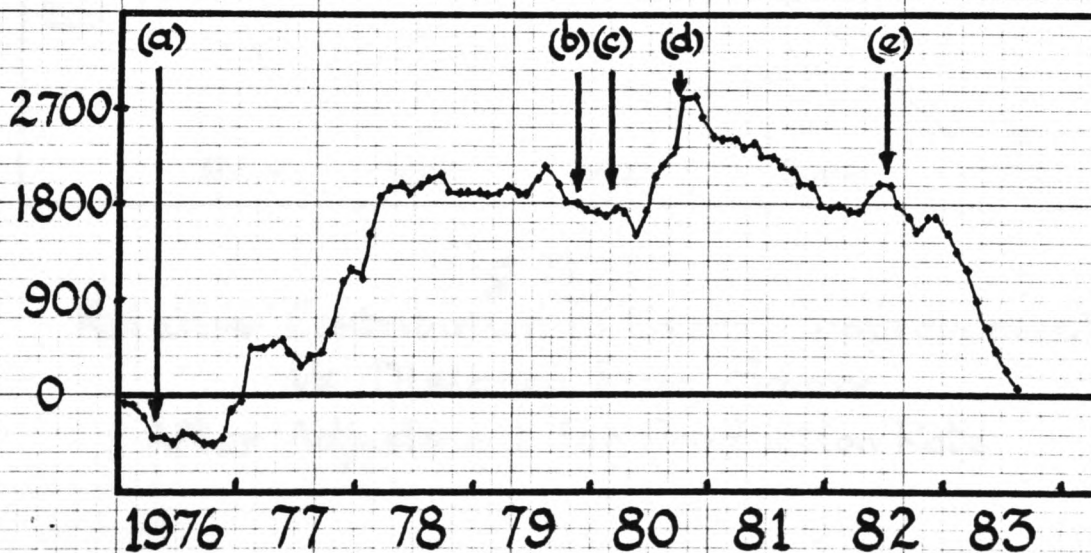


Fig.10

Conventional CuSum Chart
With Adjustment For Coke Production Rate
Nearby Gauge

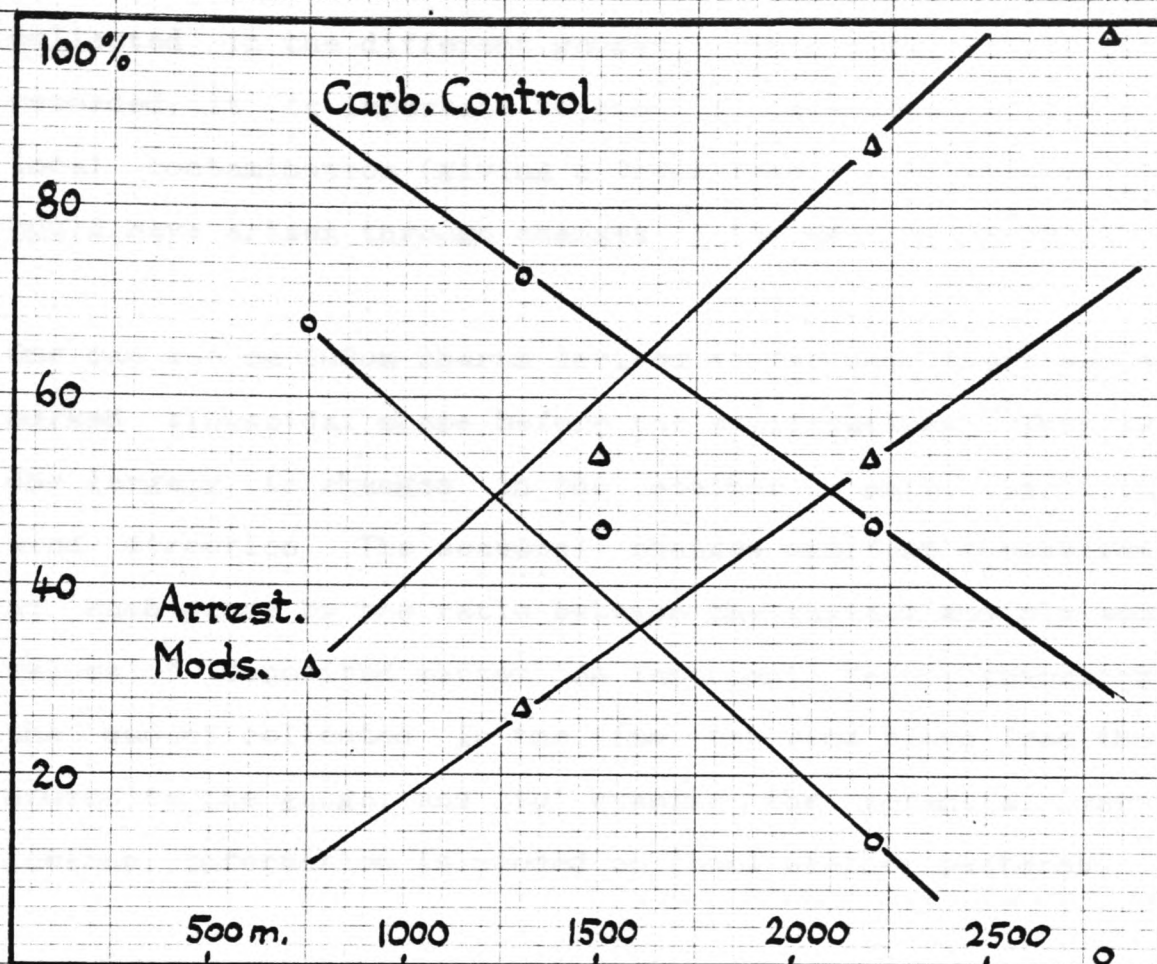


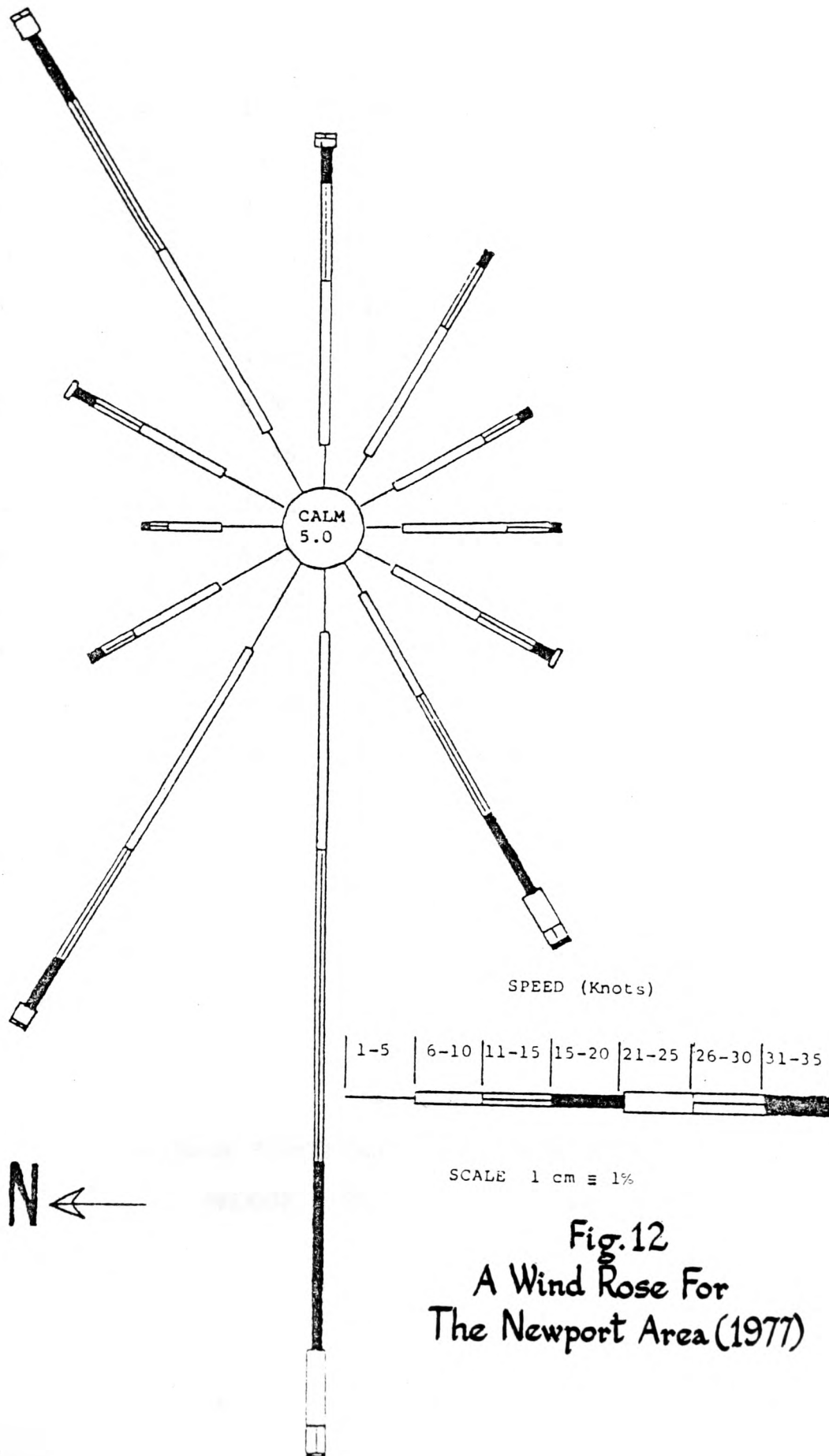
Fig 11
Relative Contribution To Overall Improvement
Vs Distance From Source
After Adjustment For Production Rate

2.9 EVALUATION OF DATA WITH SEASONAL VARIATIONS

Examination of the raw deposition data shows that in any month there may be wide variations between the amounts collected in the different gauges. When high results are recorded, it is important to know if this could be due to local contamination (giving a freak result), or whether it could have arisen through changes in the weather pattern.

One can see on CuSum charts derived so far that there was a marked sinusoidal shape before the modifications. This is due largely to changes in the weather, particularly in wind direction. The seasonal changes manifest themselves at each gauge by the ratio between the maximum and minimum values of deposited matter. An important factor governing the amount collected is the time the wind blows from the source to the gauge, and to examine the potential variations, information is needed on local weather patterns.

A wind rose for the Newport area (42) is shown in Fig.12. A special study was commissioned by HMI-API (before the present research work was envisaged), covering the meteorological data from Rhooose Airport (31) for the period 1971-1980. The results are summarised in Table 6, and are based on wind velocities 10m above ground. This study can be considered to provide information on the average weather pattern along this section of the Severn Estuary. The results are given for the 30° sectors in which the deposit gauges are sited in relation to the coke oven area, on a 10 year average basis.



	041°	101°	191°	221°	251°	Max./Min
	-070°	-130°	-220°	-250°	-280°	by Month
Jan.	12.17	9.53	6.57	12.98	18.52	2.82
Feb.	19.42	10.73	3.84	8.26	15.00	5.07
Mar.	16.99	7.58	4.93	12.52	15.15	3.45
Apr.	19.41	4.72	3.37	9.16	18.05	5.76
May	17.88	6.37	4.20	11.99	19.92	4.74
Jun.	14.04	4.45	4.13	12.69	30.45	7.37
Jul.	11.30	3.72	4.12	10.80	31.84	8.56
Aug.	15.73	5.23	4.80	10.97	20.88	4.35
Sep.	14.18	5.66	3.67	10.60	20.68	5.63
Oct.	18.27	9.67	4.88	7.29	12.61	3.74
Nov.	9.55	4.77	8.29	14.02	18.26	3.95
Dec.	11.61	6.74	8.40	14.55	18.22	2.70
Mean By						
Sector	15.02	6.59	5.11	11.34	20.03	
Max./Min.	2.03	2.88	2.49	2.00	2.52	

Table 6
AVERAGE PERCENTAGE WIND DISTRIBUTION
RHOOSE AIRPORT 1971 -1980

It can be seen that there are two prevailing wind directions, from the West and from the North East, depending on the time of year. In some months, the amount of wind coming from the two directions is about equal. Assuming that this **general** weather pattern will apply to the area around a works which is circa 30km away, there are two conclusions that can be drawn:-

- (a) The range of distributions within MONTHS for any given sector is very variable, with the max./min. ratio for the sectors varying between 2.00-2.88. Thus at any specific gauge, for a given level of emission, one may expect marked difference in deposited matter between the various months of the year, with a pattern that varies from gauge to gauge.
- (b) The range of distributions within SECTORS for any month is even more variable, with the max./min. ratio varying between 2.70-8.56. Thus, since the gauges are at different bearings around the works, marked differences in deposited matter may be found in the various gauges in any particular month for a given level of emission.

Decisions with regard to whether or not certain deposition values should be considered as freaks are difficult as a result of these seasonal weather variations, but a method of minimising their effect is essential to ease the establishment of the trend line before the modifications were carried out. This has led to the Deposition CuSum.

2.10 THE DEPOSITION CUSUM

The annual surveys of deposition values published by W.S.L. (18) show winter and summer averages. Historically, the winter averages were far higher than the summer averages, although the differences are now much less. A hypothetical smoothed graph of the seasonal variations could take the shape shown in Fig.13. This was drawn on the assumption that there were no changes in emission rates from other sources, and that the weather had been the same each year.

However, it can be proposed that in industrial locations, certain industries such as quarrying or materials handling have a greater potential for dust generation in dry summers than in wet winter months. Therefore, since the material collected in a deposit gauge depends on many local emission sources, it is probable that each particular area will have its own pattern of deposition, or "fingerprint", due to the type of activities in the locality. As a consequence, it is not feasible to generalise throughout the U.K. as to how successive months should compare in deposition values.

Nevertheless, in view of the desire to apply the CuSum technique to deposition data, the following question must be posed:- In what way could a reference value be chosen for any gauge such that a horizontal portion of the CuSum chart would arise in the absence of any major changes in the emission source under study?

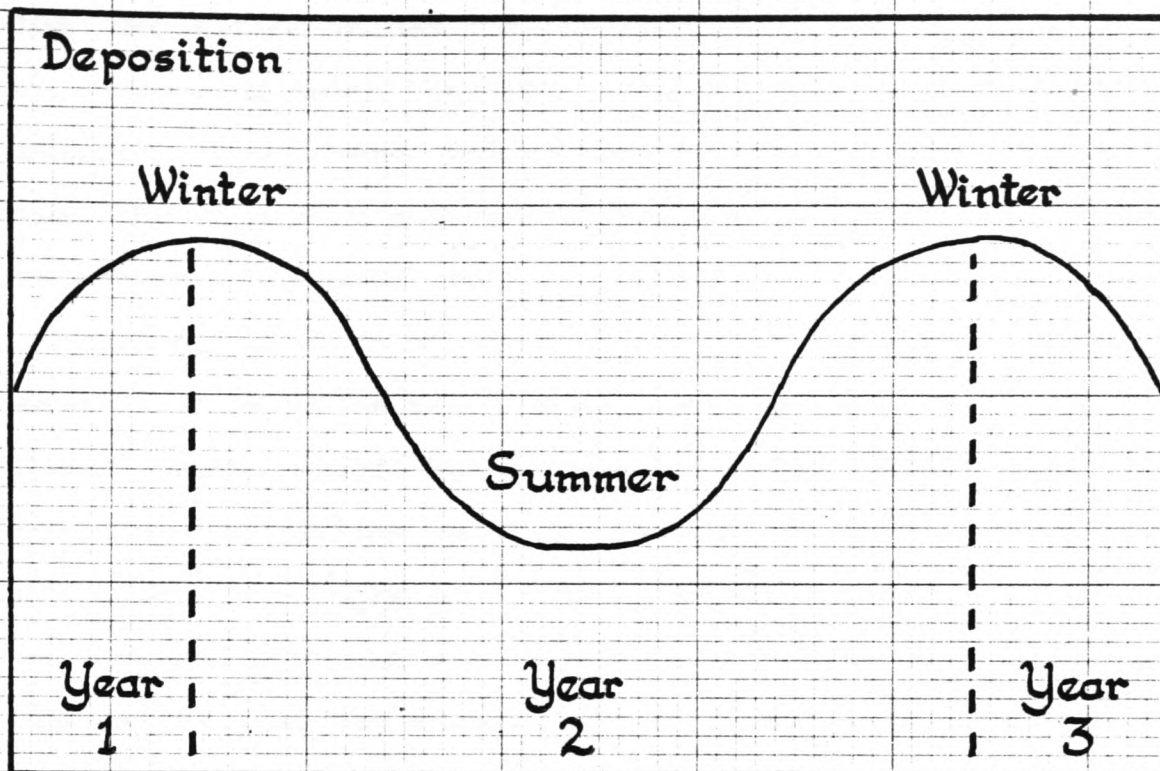


Fig. 13

A Hypothetical Smoothed Graph Of Seasonal Variations in Deposition Values

Consideration of Fig.13 shows how this may be achieved. While it may not be meaningful to compare deposition values for successive months, it is quite meaningful to compare the deposition values for one month with the value for the corresponding month one year before. In the hypothetical example chosen here, values have been taken which indicate that the values in successive years were identical. If the reference value used for any month is the value for the corresponding month of the previous year, the difference in each case would be zero, the CuSum would be zero, and the CuSum chart would be horizontal. The effect of the seasonal variations would then be entirely eliminated. In practice, the background deposition values whose effect it is desired to minimise, will not show this absolute regularity, but the effect of any background deposition will be reduced greatly, and the effect of any changes in the emission source will be enhanced.

The CuSum derived in this way is termed the Deposition CuSum. If a Deposition CuSum chart is prepared before a works comes into operation, it can be used to estimate the incremental effect on deposition values in the locality. If plotted for an existing works, using current data, it can be used to show whether emissions are improving or deteriorating, and also the point of onset of such changes. In the present study, it has been used to quantify the reduction in deposition resulting from specific modifications to arrestment equipment, and specific process changes, made at pre-determined times.

2.11 CONVENTIONS USED IN DERIVATION OF DEPOSITION CUSUM CHARTS

(i) CHOICE OF VERTICAL SCALE

The scales used have been chosen in the same way as for charting conventional CuSums, where one square on the vertical scale is equivalent to circa twice the residual S.D.

(ii) BASELINE DATA

The data for the first 12 months do not appear on the Deposition CuSum chart, but are used to provide the comparison data for the following year.

(iii) DUMMY VALUES

(a) MISSING DATA

In evaluation of historical data, where values are missing for a single month, a dummy value has been inserted equal to the mean of the values before and after, as proposed by Woodward and Goldsmith(21). If values are missing for two consecutive months, dummy values have been inserted calculated by equal interpolation between the values before and after the missing data. During the present study, there were no instances where values were missing for more than two consecutive months while known changes were being monitored.

When evaluating current data, provisional dummy values may be inserted for missing data, equal to the value for the corresponding month in the previous year. If however, the effect of a specific change is being monitored, the provisional dummy value may be estimated from the short-term trend of the CuSum chart, and then replaced the following month with a value based on the short-term means, as in the usual method.

(b) CONTAMINATED DATA

In the evaluation of historical data, where the result is recorded as contaminated, a dummy value has been inserted, calculated on the same basis as for missing data.

In the evaluation of current data, if the indications from the Deposition CuSum are that the sample is probably contaminated, the dummy value has been calculated as for missing current data in (a) above.

2.12 INTERPRETATION OF DEPOSITION CUSUM CHARTS

2.12.1 THE STEP CHANGE

The single most important feature on any Deposition CuSum chart is the appearance of a Step Change, which can be beneficial or adverse.

Consider first the situation where the chart line is reasonably horizontal, and then, due to a process change, the CuSum begins to decrease. The new trend line will slope downwards for 12 months, and will then show a further inflexion, when it reverts again to being horizontal. This will be due to the comparison with reduced values from 12 months before, and it will produce a beneficial step change. Examples of this are shown in Figs. 14(a) and (b). If the CuSum increases due to higher emission from one source, this will give rise to an adverse step change, and the month when the increase began will be quite evident.

In evaluation of cause and effect, the method requires the execution of planned modifications at specific points in time, followed by evaluation of the effect on the deposition values. If actions to reduce particulate emissions result in a beneficial step change at any gauge, then it is clear that emissions from the source under investigation had been affecting that gauge. However, if the deposition values are unaffected by the measures to reduce particulate emissions, one can say that emissions from the source under investigation are not reaching that gauge.

Examples Of Step Changes

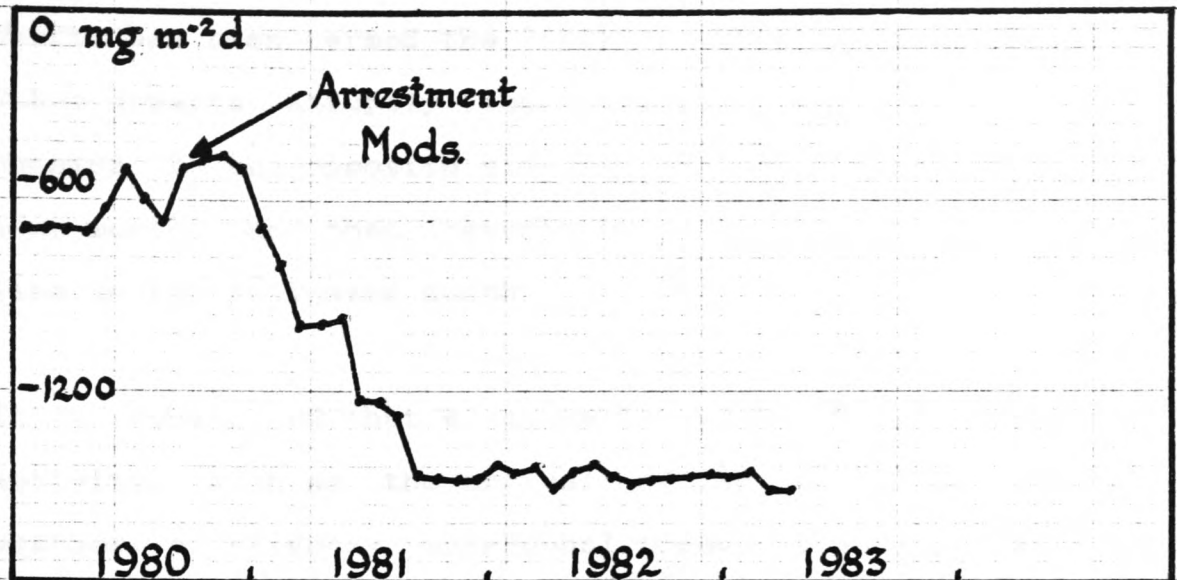


Fig. 14(a) Distant Gauge

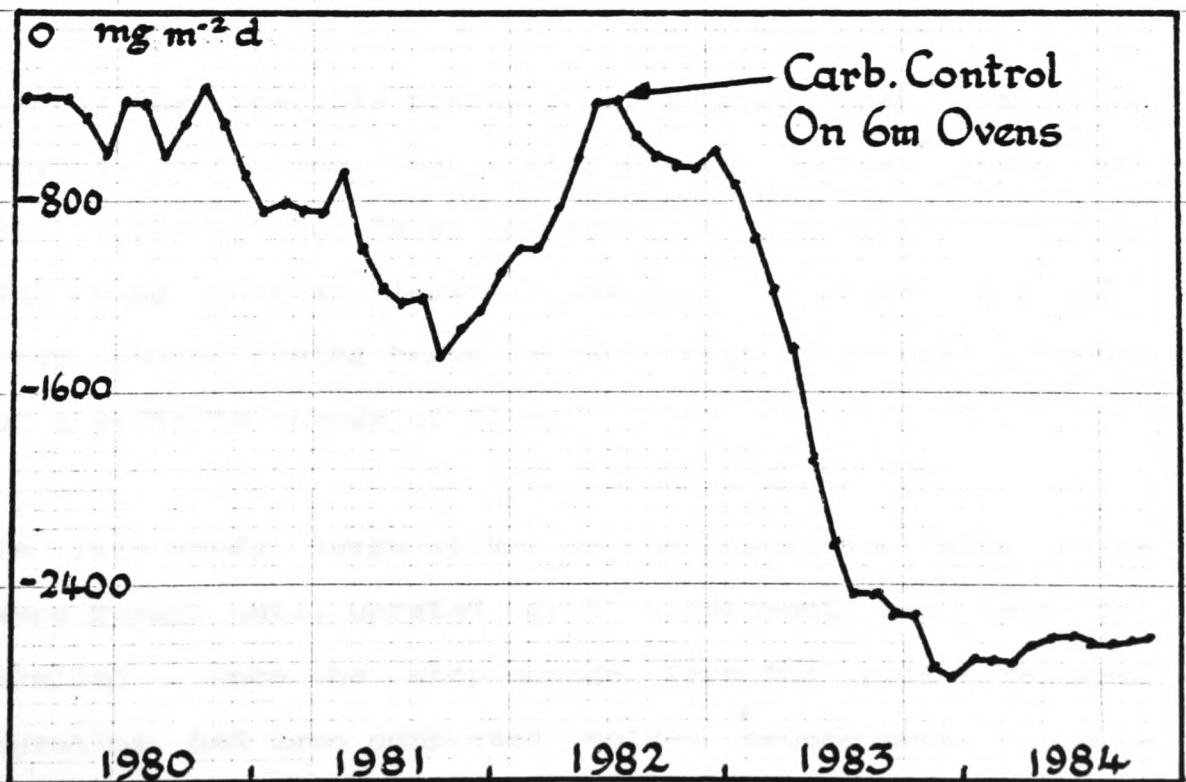


Fig. 14(b) Nearby Gauge

2.12.2 THE SPIKE

The other very common feature found on Deposition CuSum charts has been termed the "spike". This is found when the CuSum departs abruptly from the trend line for one month, changes to the opposite side of the trend line during the next month, and then reverts back to the original trend line in the following month.

It is considered that a spike is caused by an unseasonal activity, such as the arrival of the so-called seasonal weather at slightly unseasonal times, that is, early or late by comparison with previous years, or by a particular event taking place early or late, such as the annual shut-down at a works.

It is the possible presence of a spike that limits the initial conclusion that a step change may have begun, and it is prudent to delay any definite conclusion until the following month at least. However, the probability of a step change having begun is very high after only 3 months of a definite change of slope.

In this study, large spikes on the Deposition CuSum charts were common until uprated grit arrestment had been installed. Once the step change from the grit arrestment uprating had been completed, spikes became much less pronounced. This shows that inadequate grit arrestment had been a major source of variance in the deposition values.

2.12.3 THE EFFECT OF CONTAMINATION

In the case of suspected contamination, the use of the Deposition CuSum chart can give even stronger indications than usual whether or not contamination has occurred. Under normal conditions, the amounts collected in a deposit gauge are quite small, with the undissolved solids weighing much less than 1g during one month.

On a Deposition CuSum chart, the result of contamination is to displace the co-ordinates of the CuSum chart abruptly upwards, the rise being almost vertical. After 12 months, the position reverts, and the CuSum chart is then displaced abruptly downwards, to near its previous values. The relative magnitude of the movement of the co-ordinates is enhanced by the removal of the other background "noise", and it becomes even more obvious that the result is an aberration.

This does not necessarily imply that the deposited matter did not arise from the source being monitored. It may have arisen from a single major incident, but the result is clearly abnormal in the context of longer-term trends.

An example of a Deposition CuSum chart with a contaminated result is shown in Fig.15, with and without correction. This is based on actual results from a gauge sited to monitor another blast furnace coke works.

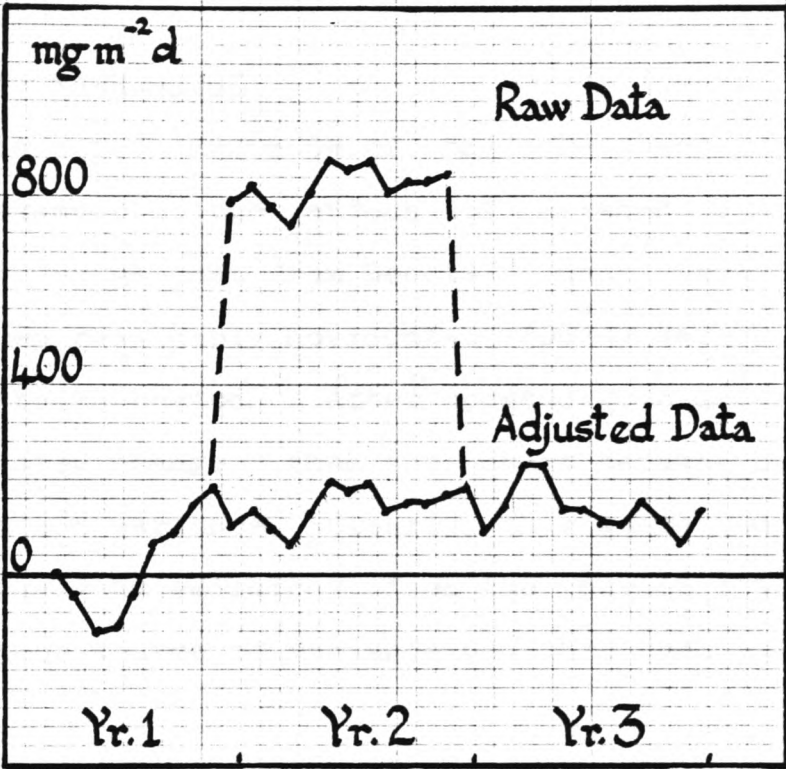


Fig.15
The Effect Of Contamination On
The Deposition CuSum

2.13 DEPOSITION CUSUM CHARTS FOR GAUGES AROUND B.S.C. LLANWERN

Two of the Deposition CuSum charts around B.S.C. Llanwern have been chosen to indicate how they can be used to evaluate the effect of the process changes.

2.13.1 NASH GAUGE

This is sited 2200m SW of the coke ovens, and provides a good example of the effect of uprated grit arrestment. Fig.16 shows that from Dec.1977 until Sept.1980 the chart had been reasonably horizontal. (Dummy values were used for the strike period.) After uprated grit arrestment, came a clear step change, then the chart became horizontal with only minor variance. Clearly, this gauge had been affected previously by emissions from the quench towers, and that the major source of variance had then been removed.

Carbonisation Control was introduced on the 4m ovens in Nov. 1981, and on the 6m ovens in July 1982. Neither change had any noticeable effect on the chart. Thus, emissions from oven discharges do not significantly affect this gauge. In April 1983, an additional battery of 4m ovens was brought into operation, while maintaining the same overall production rate from the 4m batteries. This caused a reduction in carbonisation temperature, which reduced the emissions from the quench tower, leading to a further modest reduction in deposition values. This is discussed in more detail in Chapter 3.

Meanings of subscripts given in Fig.6

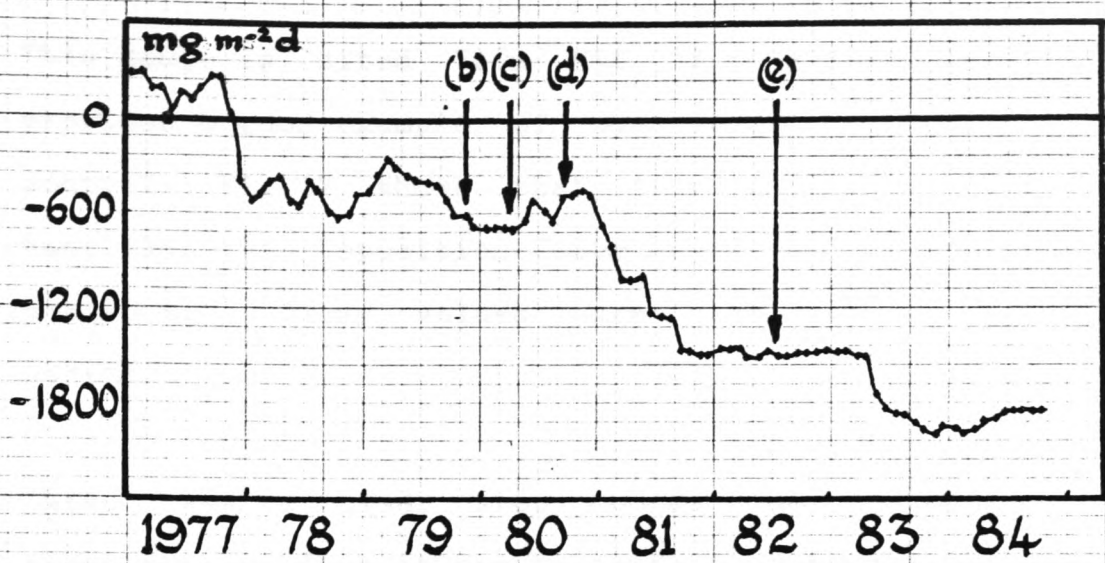


Fig.16

Deposition CuSum Chart
Nash Gauge



Fig.17

Deposition CuSum Chart
Llanwern Gauge 1

2.13.2 LLANWERN GAUGE No.1

This gauge is sited 750m NNE of the coke ovens, and provides a good example of the effect of carbonisation control. Fig.17 shows that from early in 1979 until Sept.1980 the Deposition CuSum chart had been essentially horizontal. (Dummy values were used during the strike period.)

There was a clear step change due to uprated grit arrestment. Thus it can be said that this gauge had been affected previously by emissions from the quench towers.

However, it can also be seen that the introduction of carbonisation control on the 4m ovens apparently led to an increase in the deposition values! This was evidently not due to emissions from discharges of the 4m ovens, where visual appearance had been much improved. It may have arisen from marginal reductions in carbonisation period on the 6m ovens.

From July 1982, carbonisation control on the 6m ovens led to a very pronounced step change, after which the chart became horizontal with little variance. It is clear that this gauge had been affected to a marked extent by emissions from oven discharges, but that the major sources of variance had then been removed.

The average monthly change in the deposition value can be obtained simply by dividing the magnitude of the step change by 12.

The examples chosen show that when the major sources of variance have been removed, the value of the CuSum when the chart is horizontal can be found with little error.

However, the value of the CuSum at the beginning of the step change is prone to more error because of the greater variance, and a mid-line has been chosen. The anomolous data for the strike period also presents a difficulty in the evaluation of the effect of the uprated grit arrestment. Further experiments are described in Chapter 3 to verify this effect at other works.

The reductions in the average monthly deposition values, as estimated by the Deposition CuSum technique are shown in Fig.18. This confirms the earlier finding that the emissions from oven discharges are the most significant source for the nearby gauges, and that emissions from quench towers also affect gauges much further afield, where the effect of oven discharge emissions is not significant.

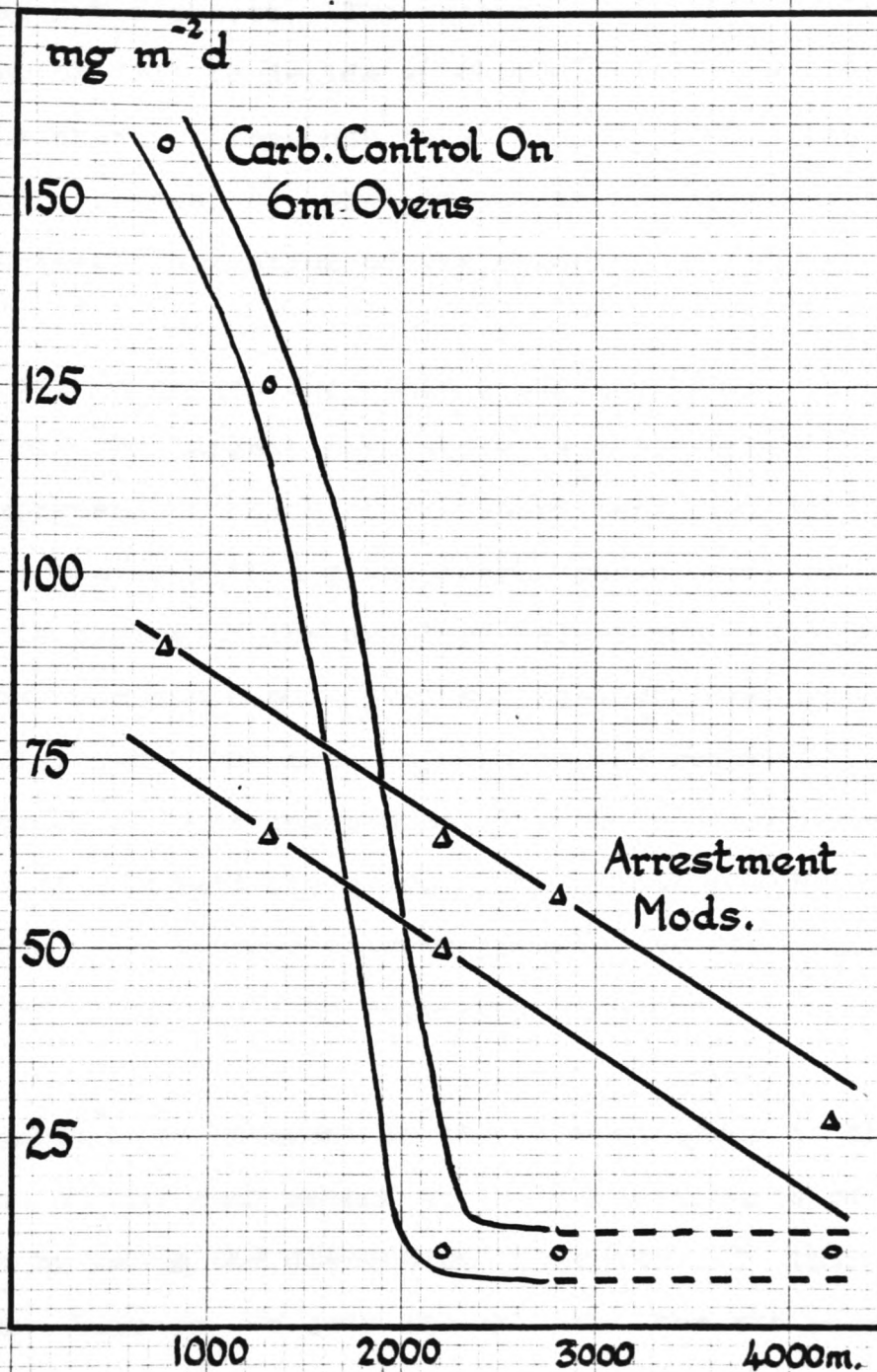


Fig. 18

Absolute Reductions Due To Control Measures As Evaluated By The Deposition CuSum Technique.

2.14 THE STATISTICAL SIGNIFICANCE OF THE STEP CHANGE

Consider the "post mortem" method of evaluation of conventional CuSum charts. Two methods are given by Woodward and Goldsmith (21) to decide whether a particular turning point on the chart corresponds to a real change in the mean value of the process, or whether it is no more than a random short-term fluctuation of the sequence.

The method chosen for this study is their "span" method. In this the largest cumulative sum (irrespective of sign) is expressed in units of the short-term standard deviation, and compared with a given graph, shown overleaf as Fig.19. This is a plot of the expected values and tails percentiles of the maximum cumulative sum against the number (n) of results, when the mean is used as the reference value, and the results come independently from a Normal Distribution of unit standard deviation. It is thus possible to assess whether the largest observed cumulative sum is larger (or smaller) than would be expected by chance.

Of particular interest in the present study is the application of the span method to subsidiary parts of the CuSum chart by using the dissection property of this type of chart. Suppose we join the q th and the s th points on the chart by a straight line as shown in Fig.20. Then for all values of q and s such that $0 \leq q < s \leq n$, the distance of the r th point ($q \leq r \leq s$) of the chart from the line is given by:-

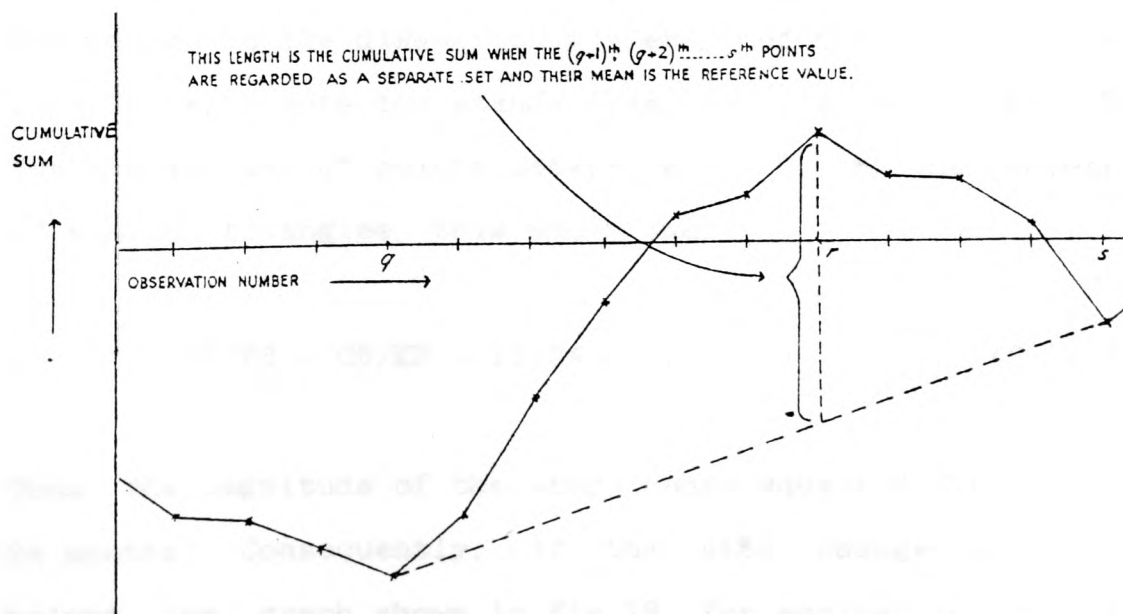
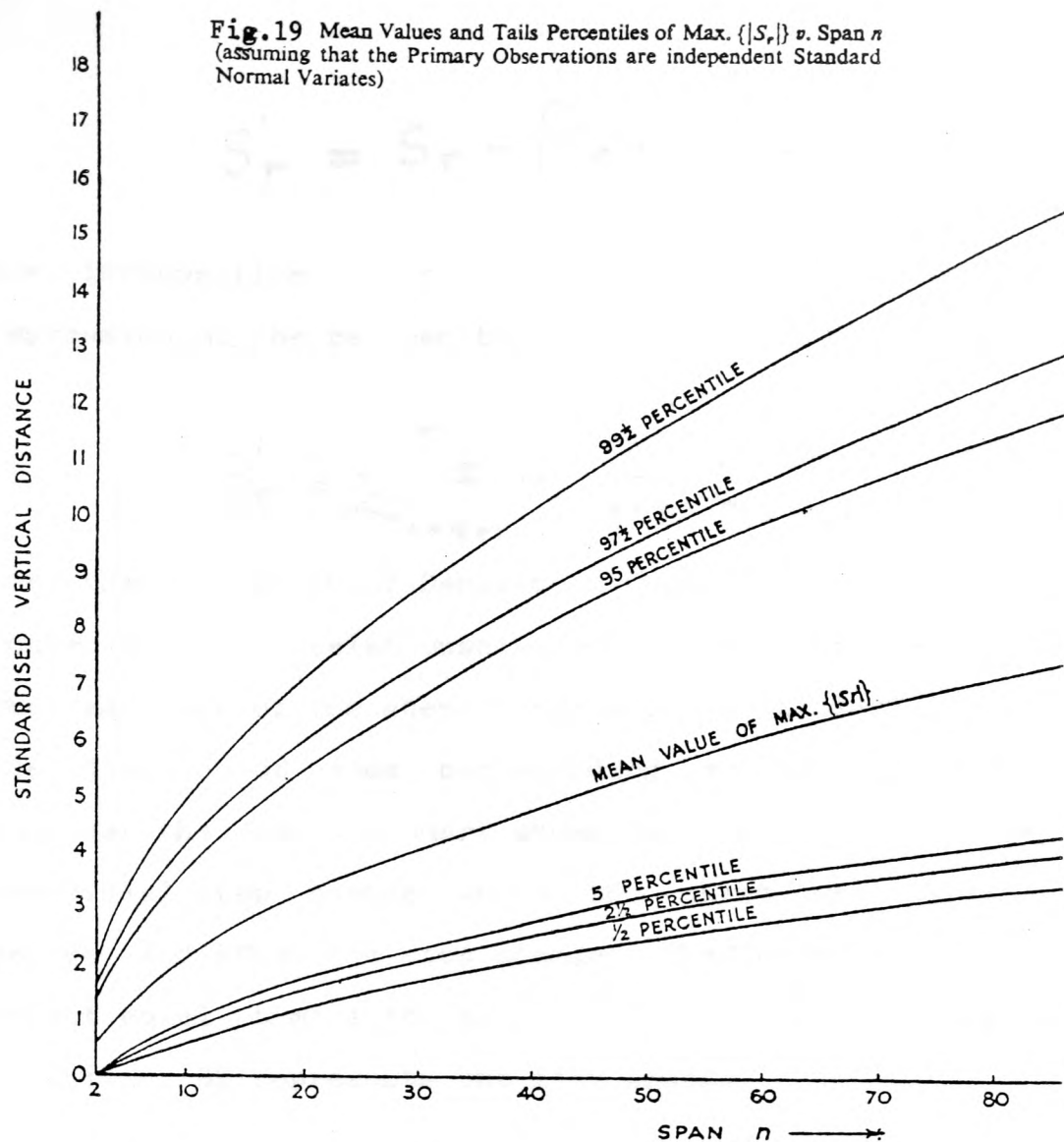


Fig.20 Dissection Property of Cumulative Sum Charts

$$S'_r = S_r - \left[S_q + \frac{r-q}{s-q} (S_s - S_q) \right] \quad (2.14.1)$$

Now, irrespective of the chosen reference value, this expression may be reduced to:-

$$S'_r = \sum_{i=q+1}^r x_i - \frac{r-q}{s-q} \sum_{i=q+1}^s x_i \quad (2.14.2)$$

For the evaluation of Deposition CuSum charts, it would be convenient if a relationship could be determined between the magnitude of the step change and the standardised vertical distance of some corresponding sub-set of results. Consider the example chart shown in Fig.21, which shows a beneficial step change where the chart was horizontal before and after the step change. The letters A to D represent equal time intervals of 12 months. In this construction, BE represents the step change.

According to the dissection property of CuSum charts, the line CF represents the standardised vertical distance (SVD) for the sub-set of points between B and D. By the geometry of similar triangles, this shows that:-

$$CF/EB = CD/ED = 12/24 = 0.5 \quad (2.14.3)$$

Thus the magnitude of the step change equals 2 SVD when n= 24 months. Consequently, if the step change value is halved, the graph shown in Fig.19 for estimating the significance of the change, can be used directly.

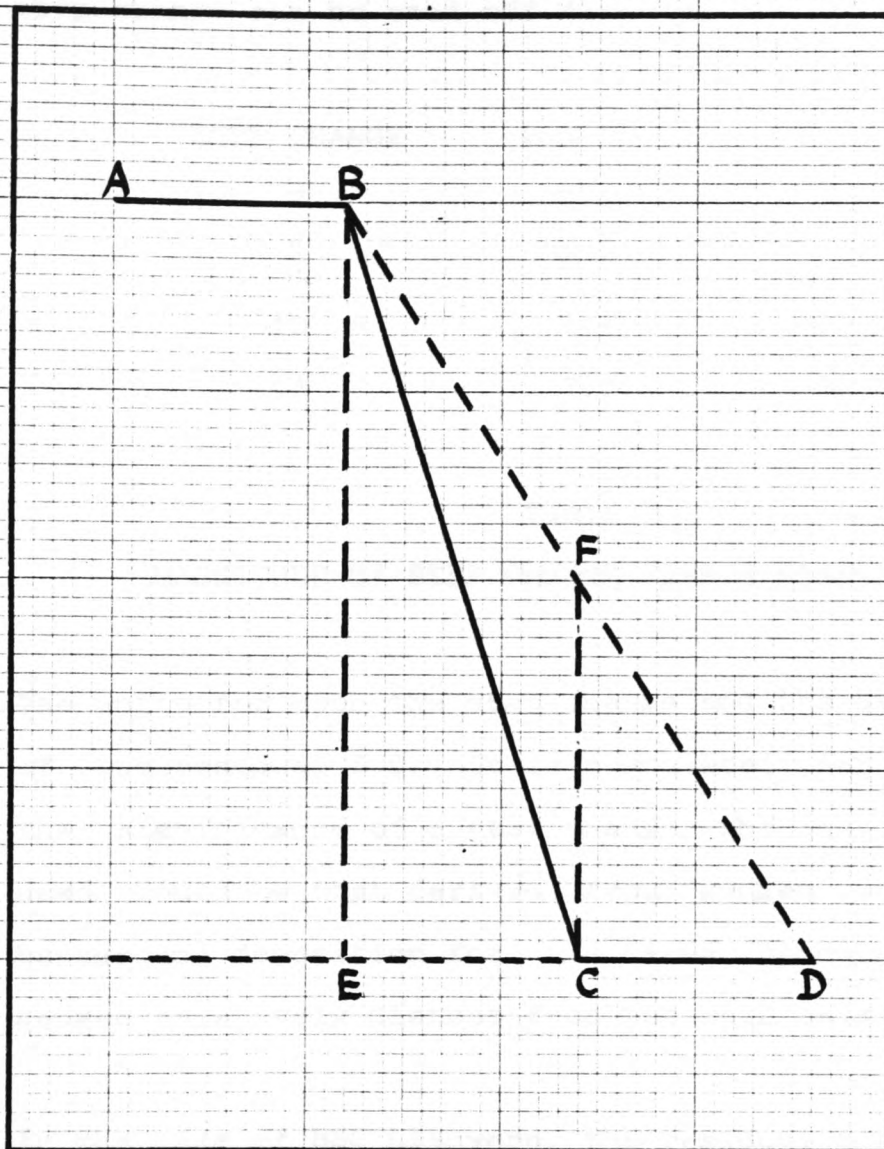


Fig. 21
Relationship Between Step Change
And
Standardised Vertical Distance

For $n=24$, the values shown in Table 7 can be derived, and since the vertical scale on the Deposition CuSum chart is in units of $2 \times \text{Residual S.D.}$, the significance of the step change can be read off directly:-

STEP CHANGE	S.V.D.	PERCENTILE
7	3.5	50
12	6.0	95
13	6.5	97.5
15	7.5	99.5

Table 7
MAGNITUDE OF STEP CHANGE VERSUS SIGNIFICANCE

The units for both the step change and the SVD are in terms of the residual S.D. It is postulated that, in evaluating the significance of a step change, the residual S.D. to be used should be that derived from gauges which show the background deposition for the area concerned, that is, gauges relatively distant from the main emission sources.

In the case of BSC Llanwern, the residual S.D. for the more distant gauges was in the order of $25 \text{ mg m}^{-2} \text{ d}$ after both the changes had been implemented. Using this data, Tables 8 and 9 demonstrate the significance of the step changes due to grit arrestor modifications and carbonisation control respectively.

Site	Absolute Step Change mg m ⁻² d	Step Change 2 x S.V.D.	Percentile
Llanwern I	1100	22	> 99.5
Llanwern II	800	16	> 99.5
Hartridge	350	7	> 97.5
Nash	800	16	> 99.5
Bishton I	600	12	> 99.5
Bishton II	700	14	> 99.5
Langstone	350	7	> 97.5

Table 8

GRIT ARRESTOR MODIFICATIONS
SIGNIFICANCE OF STEP CHANGE

Site	Absolute Step Change mg m ⁻² d	Step Change 2 x S.V.D.	Percentile
Llanwern I	2000	40	> 99.5
Llanwern II	1500	30	> 99.5
Hartridge	< 100	< 2	N/S
Nash	< 100	< 2	N/S
Bishton I	< 200	< 4	N/S
Bishton II	(+ve)	-	N/S
Langstone	< 200	< 4	N/S

Table 9

CARBONISATION CONTROL
SIGNIFICANCE OF STEP CHANGE

2.15 RELATIONSHIP BETWEEN DEPOSITED AND SUSPENDED PARTICULATE MATTER

Newport B.C.(35) operate sites around B.S.C. Llanwern for measuring "smoke" and SO₂ as part of the National Survey (17). One of the sites is adjacent to a gauge used for measuring deposited matter some 1.5km NW of the coke ovens. An evaluation has therefore been carried out to see if the "smoke" results were affected by the changes at the coke oven plant. A reduction in smoke levels could be expected following the improvement in visual appearance of the discharges after implementing carbonisation control.

The smoke, or suspended particulate matter, is determined on a daily basis, and published as monthly averages, in $\mu\text{g m}^{-3}$ of air sampled. The method is based on reflectometer readings from a filter paper which had removed the "smoke" from the air stream. This is a different method from that for deposited particulate matter, and is determined by different staff, so it is a useful independent check. (Deposited particulate matter is determined by the County Analyst on a single sample collected over a month.)

Results for suspended particulate matter were available at this site from April 1977 until August 1983, when use of the site was discontinued. Evaluation of the raw data by the conventional CuSum technique indicated a very marked seasonal variation, as shown in Fig. 22. However, the changes in slope are detectable, and they correspond to the

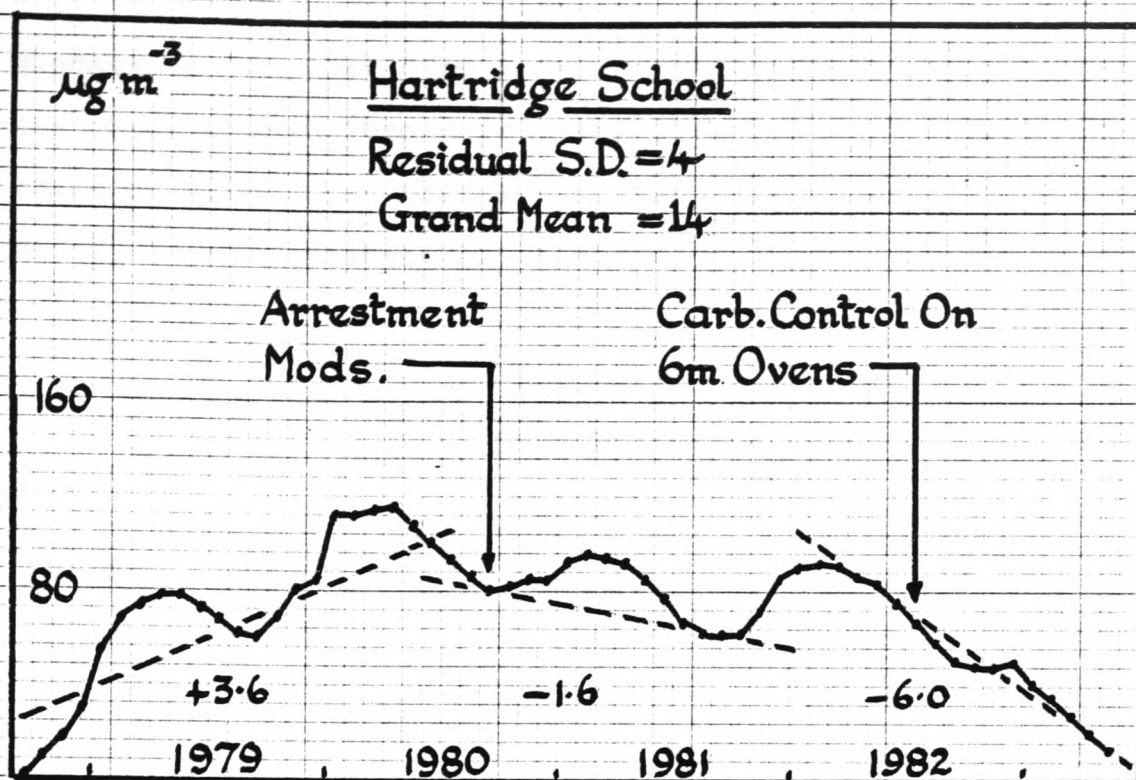


Fig.22
Conventional Cusum Chart
Based On
Smoke Monitor Data.

changes at the coke oven plant. Estimates of the effect of the changes have been made, and in Table 10 these are compared with the effect on the deposited particulate matter at the adjacent gauge:-

	Suspended Part.Matter $\mu\text{g m}^{-3}$	Deposited Part.Matter $\text{mg m}^{-2}\text{d}$
Change after Arrestment Mods.	-30%	-31%
Change after Carb. Control.	-25%	-40%

Table 10.

RELATIONSHIP BETWEEN DEPOSITED AND SUSPENDED
PARTICULATE MATTER

Construction of the Deposition CuSum shown in Fig.23 minimises much of the seasonal variation, and shows the effect of the changes more clearly. It is apparent that emissions from coke oven discharges made a significant contribution to the "smoke" readings in the locality, and the quench emissions also had a noticeable effect. The reduction due to carbonisation control produced a step change of circa 8.5 SVD, which is highly significant. The step change due to grit arrestment modifications is more difficult to assess, but is probably significant, although no correction was made for the 1980 strike period.

Hartridge School

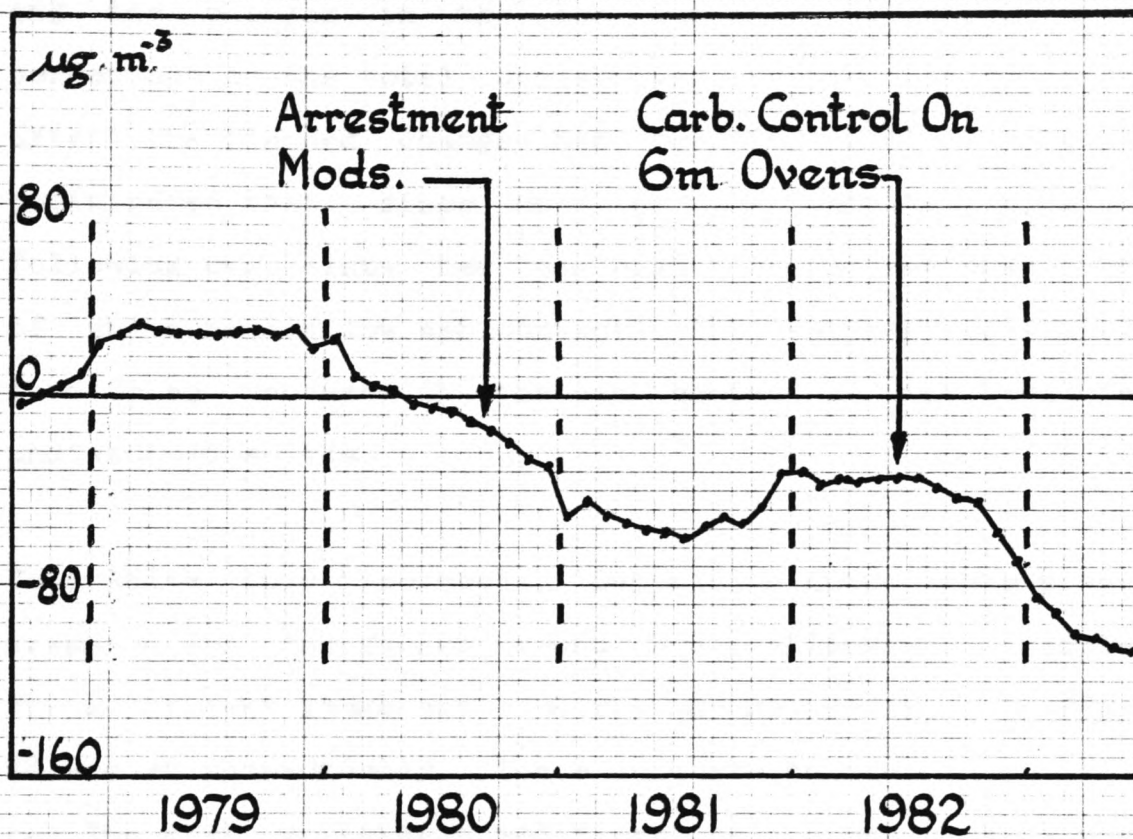


Fig. 23

Deposition CuSum Chart
Based On
Smoke Monitor Data

2.16 THE COMPOSITION OF DEPOSITED PARTICULATE MATTER

No detailed chemical analyses have been made of the particulate matter collected in the BS deposit gauges around the iron and steel works, but some pointers towards the composition of the two sources can be obtained by evaluating the changes in the ash content, expressed as a percentage of the total undissolved solids, which arose after the planned changes had been implemented. It was anticipated that, since most of the material examined following complaints had been high in coal and coke (both of which have a low ash content), the abatement work would lead to an increase in the ash content of the remaining undissolved solids.

To examine this hypothesis, Deposition CuSum charts were prepared for the gauges around B.S.C. Llanwern. Examples for a distant gauge and a nearby gauge are shown in Figs. 24 and 25 respectively. These indicate that:-

- (a) The grit arrestment modifications did not cause a significant change in the ash content in either gauge. If anything, there was a modest increase, suggesting that the ash content of quench tower emissions was low.
- (b) Carbonisation control on the 6m ovens caused a significant **reduction** in the ash content in the nearby gauge but no significant change in the more distant gauge. This suggests that the material emitted during oven discharges is relatively higher in ash content (mineral matter).

(a) Arrestment Mods.
(b) Carbonisation Control

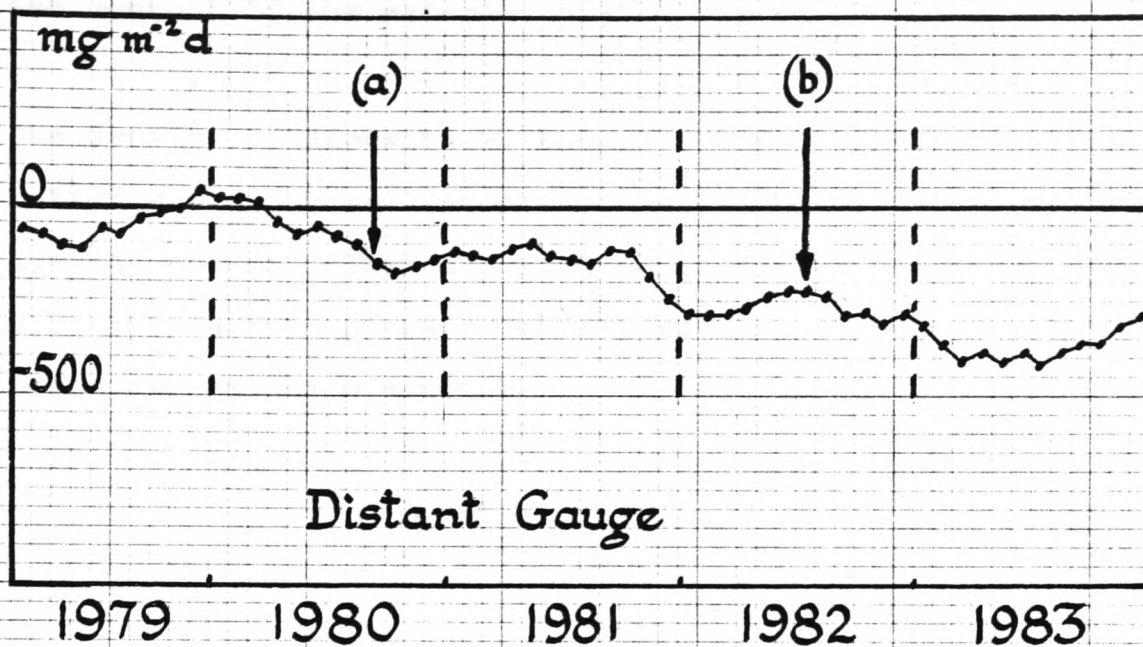


Fig. 24

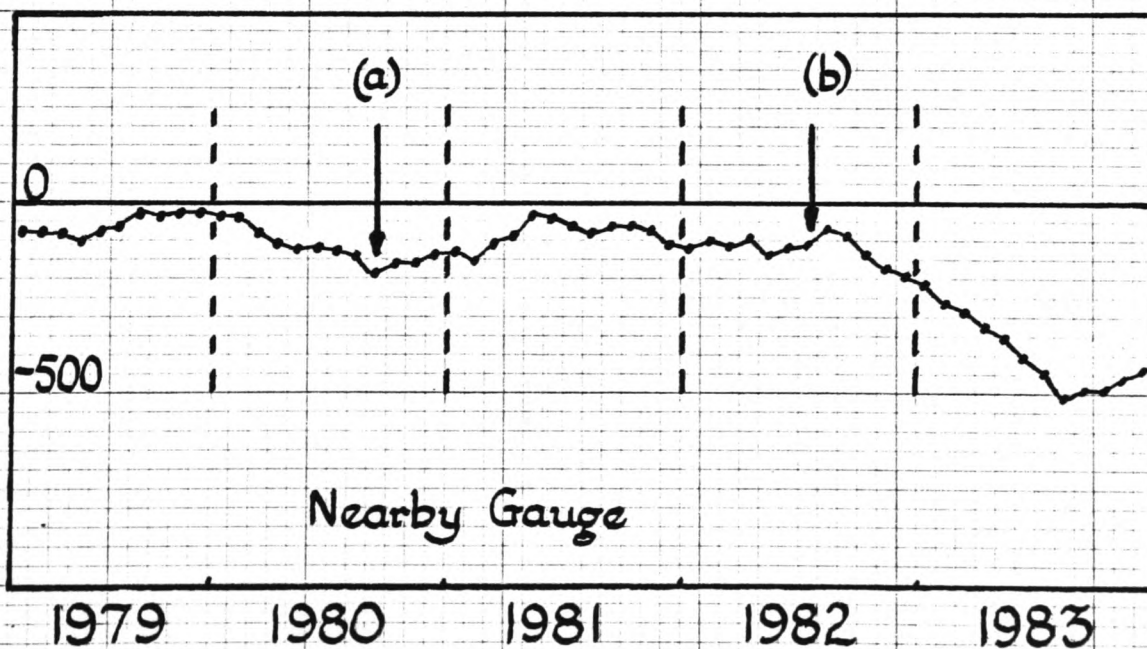


Fig. 25

Deposition CuSum Of Ash As Percent
Of Undissolved Solids

Based on the summated deposition values and corresponding ash contents of material collected in the two nearest gauges in Llanwern village, it can be estimated that the ash content of the material abated was circa $85 \pm 11\%$.

The density of deposits with such a high content of mineral matter would be well in excess of deposits emanating from quench towers. This difference in density would be a significant factor in the different spatial distributions from these two emission sources.

3.1 DEVELOPMENT OF THE KNOWLEDGE OF GRIT ARRESTMENT

3.1.1. Most of the early development work on grit arrestment was done in the U.K., following experiments on cooling towers. Methods of eliminating drizzle from such towers were described by Chilton(5). Various types of packing were tested under laboratory conditions at nominal air velocities of $0.9-2.1 \text{ m s}^{-1}$. At 2.1 m s^{-1} , droplets up to $500 \mu\text{m}$ diameter were elutriated.

Inclined wooden louvres of section $76 \times 12.5 \text{ mm}$ were found to be effective. The various types tested are shown in Fig.26(a). The design chosen for field trials was based on arrangement C, with the following parameters:-

$$\theta = 70^\circ$$

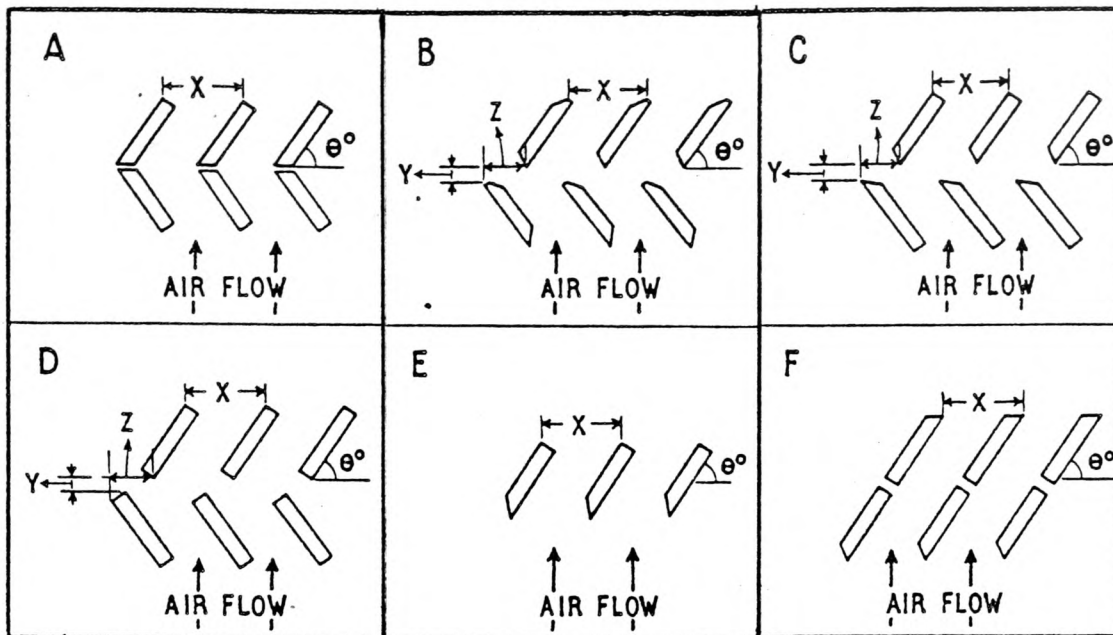
$$X = 70 \text{ mm}$$

$$Y = 12.5 \text{ mm}$$

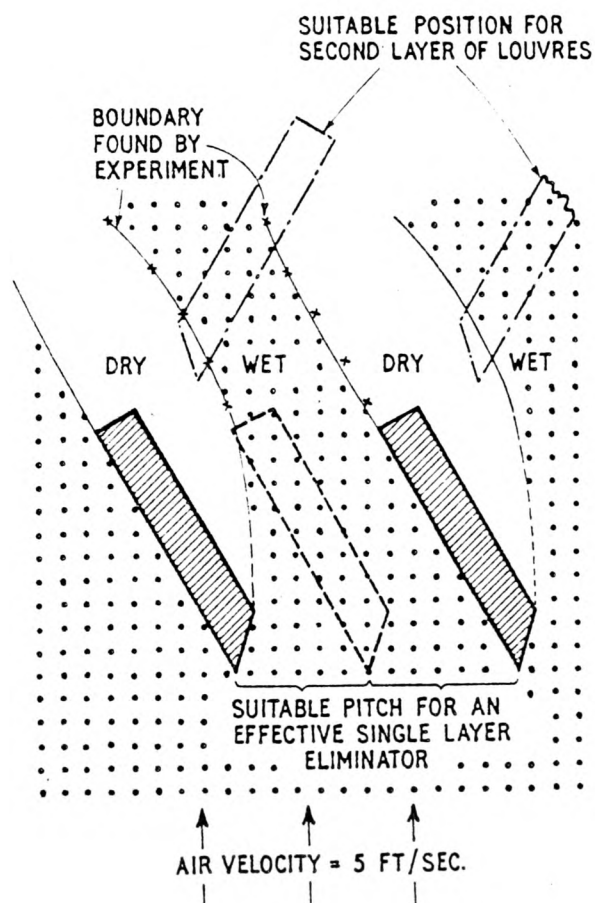
$$Z = 25 \text{ mm}$$

In full-scale trials, the reduction in maximum precipitation rate, after fitting arrestors, was 99%.

It can be seen from Fig.26(b) that the design did not cater for complete overlap between the two layers. Use was made of the wet/dry boundary layer for water droplets found by photography under intense lighting in the laboratory, at the relatively modest air velocities prevalent in cooling towers.



(a)



(b)

Fig. 26
Eliminators used by Chilton

This absence of overlap continued in later developments by other workers (see later). It was considered by Chilton(5) that in special cases, a single layer of louvres might suffice. A smaller pitch would then be needed, as shown in Fig.26(b).

Some experimental work was done with angles of inclination down to 45° . Such arrangements were very effective, but the pressure drop was much higher (up to 19 velocity heads) and these were not thought suitable for natural draught towers.

3.1.2 Louvres based on Chilton's work were installed in 1954 in quench towers at Wandsworth Gas Works. Their effectiveness in removal of water droplets was reported by Portchmouth (7). The following design parameters were used:-

$$\theta = 70^\circ$$

$$X = 58\text{mm}$$

$$Y = 25\text{mm}$$

$$Z = \text{Not reported}$$

These dimensions also do not provide for overlap. A comparison of operating results is shown in Table 11. No determinations were made of dust carry-over, but it was assumed that "the louvres would remove, with a similar efficiency, solid particles of the same size range as the water droplets". (The emission contained 20% of droplets $>500\text{ }\mu\text{m}$ diameter.)

	Cooling Tower Quench Tower	
	Chilton	Portchmouth
Mean Upward		
Velocity m s^{-1}	2.13	3.84
Water Loading		
$\text{g s}^{-1}\text{m}^{-2}$	1250	2840
Water Carry-over		
$\text{g s}^{-1}\text{m}^{-2}$	6	95-110
Average Drop		
Diameter μm	370	396
Efficiency For		
Water Droplets %	95	77

Table 11
COMPARISON BETWEEN COOLING TOWER AND QUENCH TOWER

3.1.3 The Clean Air Act 1956(6) caused the coke-making process to become registrable under the Alkali Act(1), and the significance for the industry was outlined by Hall and Sandall(10). They mentioned the lack of suitable means for measurement of grit and dust emissions.

3.1.4 In 1957, Thring and Sarjent(8) reported on the spatial distribution of dust emissions from quench towers serving 4m ovens. The dust entrained with the steam could carry 500-600m. They stated that gentler sprays reduced the dust emissions.

- 3.1.5 The first detailed experiments on grit arrestment were described in 1959 by Harris et al(12), based on parallel-sided towers at B.S.C. Port Talbot. Wedge-wire screens, at 25° inclination, were used, irrigated continuously during the quench. This gave maximum contact surface with the grit-bearing steam. The water evaporated per quench was circa 500kg Mg⁻¹ of coke quenched. Four sampling methods were used:-
- (a) Suspended condenser. A simple device used in the early stages to give approximate results.
 - (b) Suction sampler. Isokinetic sampling was not considered practicable due to large variations in upward velocity. Single point sampling was used instead.
 - (c) Greased plate collector. Used to compare emission rates at various times during the quench. High melting point greases were needed.
 - (d) Bucket sampler. Used to collect material falling from louvres.

The authors estimated the most probable results overall, given in Table 12, with some suction sampler data from the centre bay only. The overall efficiency is similar to that anticipated by Portchmouth(7). The lower temperature with arrestment is due to the irrigation sprays. Sufficient material was collected with methods (c) and (d) to allow particle size analysis. The results are shown in Fig.27.

- (a) Greased plate with arrestment
- (b) Bucket condenser with arrestment
- (c) Greased plate without arrestment
- (d) Bucket condenser without arrestment

SIEVE ANALYSIS GRAPH SHEET

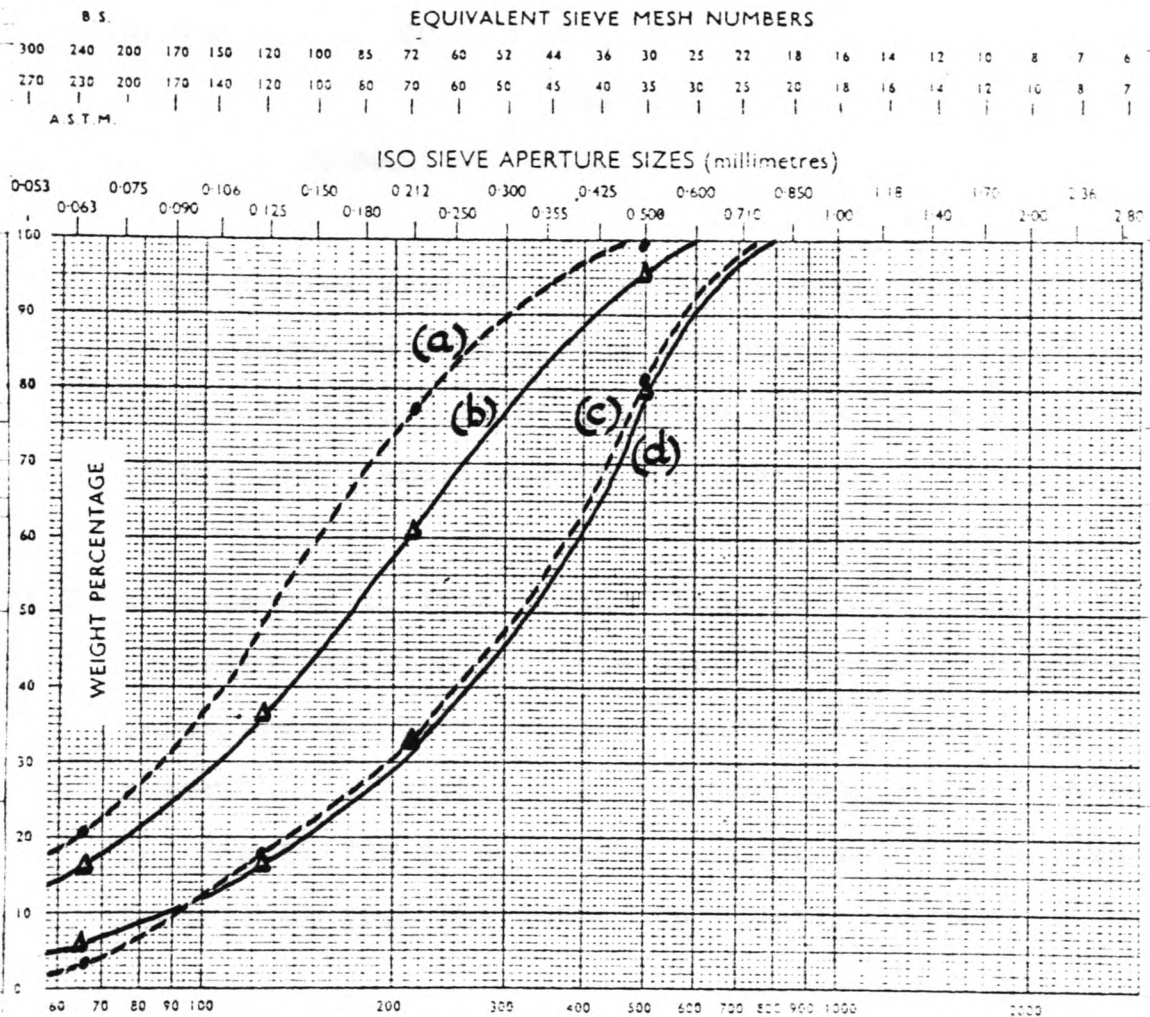


Fig. 27
Particle Size Analysis
Harris Data

Suction Sampler Results			
	Emission Rate	Max.Emission	Max.Emission
	$\text{g Mg}^{-1} \text{ coke}$	Vel. m s^{-1}	Temp. K
Open			
Tower	80	1.70	356
With			
Arrest.	20	1.27	339

Table 12

SUMMARY OF RESULTS BY HARRIS ET AL (12)

3.1.6. Quantitative studies on emission rates followed the development in 1958 of the miniature suction cyclone by the British Coal Utilisation Research Association (BCURA) for sampling grit and dust(11).

3.1.7 Experiments in 1959 by the National Coal Board (13) provided data on particle size analysis of material deposited in calm weather close to open quench towers, i.e. within 50m. Average results are shown in Fig.28 for foundry coke and blast furnace coke. Deposition from the latter is clearly coarser.

3.1.8 The first use of the BCURA equipment in quench towers was reported by Jackson and Waple(19) in 1960 at Gartsherrie Works in Scotland, to determine the effectiveness of louvre-type eliminators. They used a double bank of louvres similar to Portchmouth(7).

The parallel-sided tower was divided into 3 bays of

(a) Foundry Coke Works
(b) Blast Furnace Coke Works

SIEVE ANALYSIS GRAPH SHEET

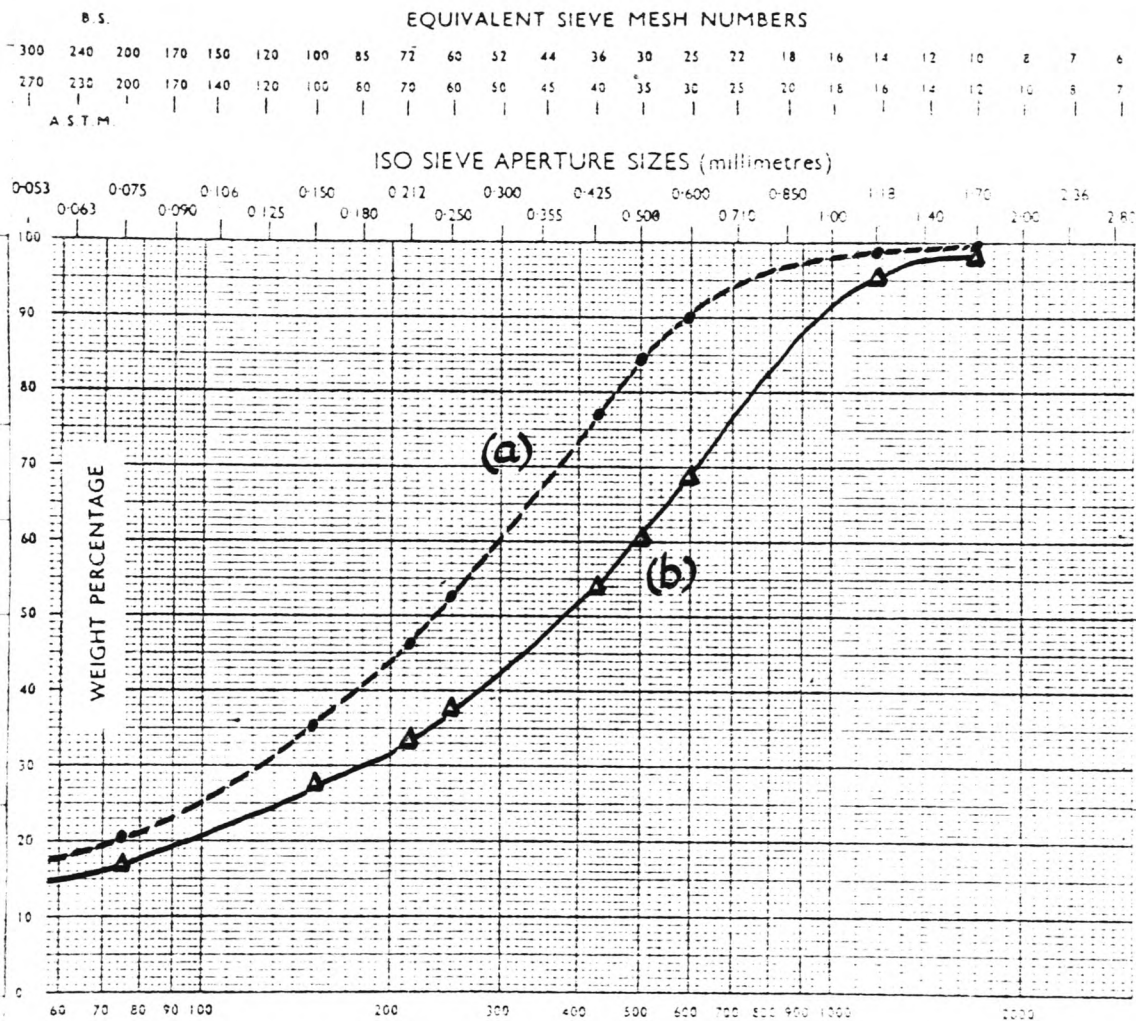


Fig. 28
Particle Size Analysis
N.C.B. Data

approx. equal size. Each bay was divided into 9 elements of equal area, and sampling was from the centre of each element. One sample was taken per quench, the locations being selected in random order. Six full replicates were done with the open tower, and four with arrestment. The emissions at a carbonisation time of 19.5h are given in Table 13:-

	Emission Rate	Max.Emission	Max.Emission
	g Mg ⁻¹ coke	Vel. m s ⁻¹	Temp. K
Open			
Tower	535	5.18	348
With			
Arrest.	268	3.81	367

Table 13

JACKSON & WAPLE RESULTS-STANDARD COKING TIME (19)

The emission rates were far higher than those reported by Harris et al(12), and the collection efficiency was lower. However, Jackson and Waple (19) reported far more material below 100µm, as seen in Fig.29. Limited tests indicated that 80% of the solids were emitted in the first 30s of the quench. (Some experiments were also done with a carbonisation time of 35.5h, which gave emission rates from an open tower of only 107g Mg⁻¹.) Efficiencies of baffles of differing materials and locations were reported as in Table 14.

- (a) With Arrestment
 (b) Without Arrestment
 (c) Deposits In Tower

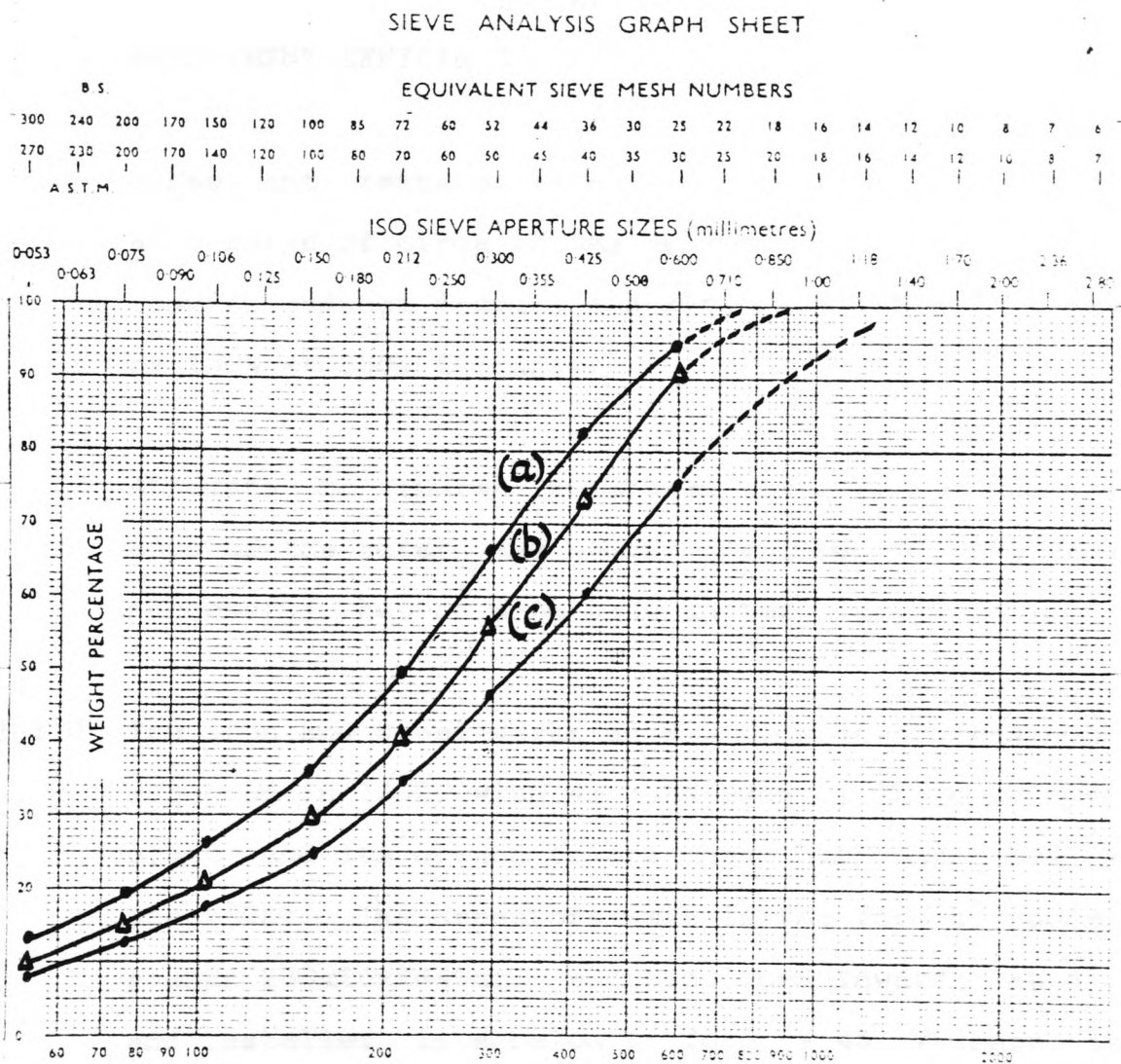


Fig. 29
Particle Size Analysis
Jackson & Waple Data (19)

	High	Low
	Position	Position
Timber Louvres	63%	18%
Asbestos Louvres	22%	10%

Table 14

ARRESTMENT EFFICIENCY OF VARIOUS LOUVRE TYPES (19)

Subsequent tests on water droplet emissions indicated rates of circa 15.5kg Mg^{-1} of coke. High timber louvres reduced droplet deposition by 96% at 50m and by 100% at 100m distance.

Attempts to simulate a tapered tower by sealing the tops of the outer bays were reported to be very successful, but no data were quoted.

3.1.9 The iron and steel works at B.S.C. Llanwern was constructed in 1962, with 4m coke ovens. The coke oven plant and its quench towers have been described by Steer(25). The arrestors were in the form of wooden planks 230x25x2640mm, each inclined inwards at 5° , and installed in echelon to form a 45° V-shape, as shown in Fig.30, which gives an elevation along the axis of the rail track.

(6m ovens were installed when the works was expanded in 1976. The new quench tower was of the same basic design, but larger overall.)

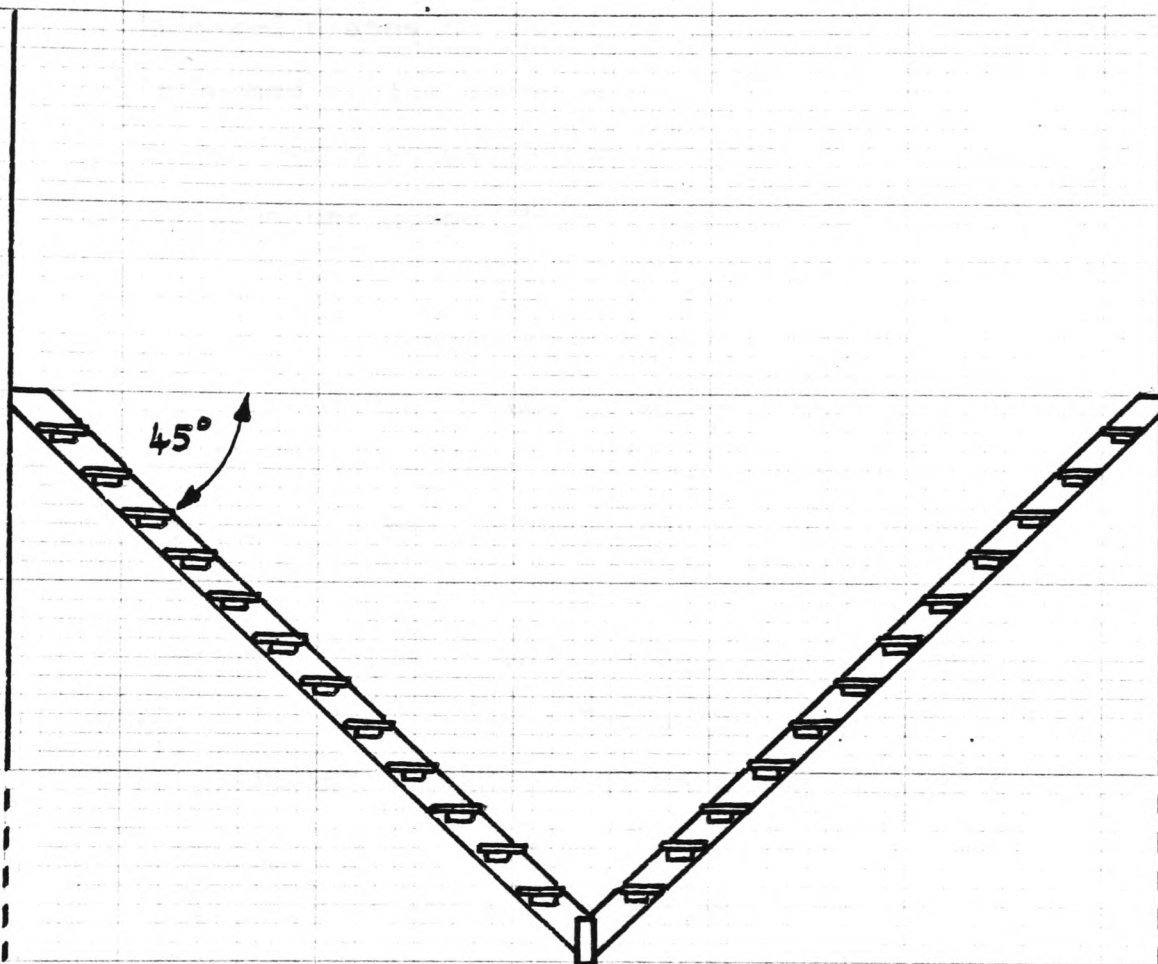


Fig.30
Elevation Of Grit Arrestment System
At B.S.C. Llanwern

3.1.10 Experiments to determine the effect of grit arrestors on external deposition were described by Hall and Nellist(23) in 1962. They used 300mm diameter greased plates to measure deposition from single quenches at distances up to 92m downwind of the tower, with a pathwidth of 23m. The average deposition per quench (mg m^{-2}) is given in Table 15:-

	Distance From Tower			Computed Deposition
	23m	46m	92m	per Quench (g)
Open				
Tower	88	129	125	476
With				
Arrest.	127	127	88	463

Table 15

SUMMARY OF RESULTS BY HALL AND NELLIST (23)

The calculated depositions per quench for distances up to 92m only corresponded to emission of circa 36g Mg^{-1} of coke. There was a change in spatial distribution on fitting arrestors, the highest results then being found nearer the tower. No tests were done at greater distances, but the deposition at a BS gauge sited 230m from the tower fell by $90\text{mg m}^{-2}\text{d}$, attributed to the arrestors.

3.1.11 Experimental work on a 4m oven tower was reported in 1967 by Fullerton(26). The tapered quench tower was 30.5m high with an upper exit 21m in area. The

peak emission velocity was 11m s^{-1} at 344K . Internal greased plate sampling was used, and louver combinations were tested at angles of 70° and 45° . Efficiencies were quoted as 60% and 85% respectively. Particle size analyses were done on the collected solids, the results being shown in Fig.31, which reveals much more of the coarser fraction than in earlier reports, for an open tower.

3.1.12 Similar improvements were reported by Geminder(27) in 1968. Using 60° louvres, the emission rate fell from 770 to 92g Mg^{-1} , an efficiency of 92%. Parallel tests showed that about 75% of the water droplets falling in the vicinity of the open tower were prevented by installation of arrestors. The dissolved solids content had been found to be up to 350g Mg^{-1} of coke, and hence it was postulated that emissions of dissolved solids would fall by the same percentage. No tests to verify this were done.

3.1.13 Also in 1968, a report on "Air Pollution By Coking Plants" was produced by a "group of experts on coking" within the Economic Commission For Europe(28). No developments in grit arrestment were reported which have not been covered previously in this section.

3.1.14 1973 saw the setting up of a Coke Plant Design Study Group by B.S.C. Ltd.(32), which included the British

Without Arrestment

SIEVE ANALYSIS GRAPH SHEET

B.S.			EQUIVALENT SIEVE MESH NUMBERS																				
300	240	200	170	150	120	100	85	72	60	52	44	36	30	25	22	18	16	14	12	10	8	7	6
270	230	200	170	140	120	100	80	70	60	50	45	40	35	30	25	20	18	16	14	12	10	8	7
A.S.T.M.																							

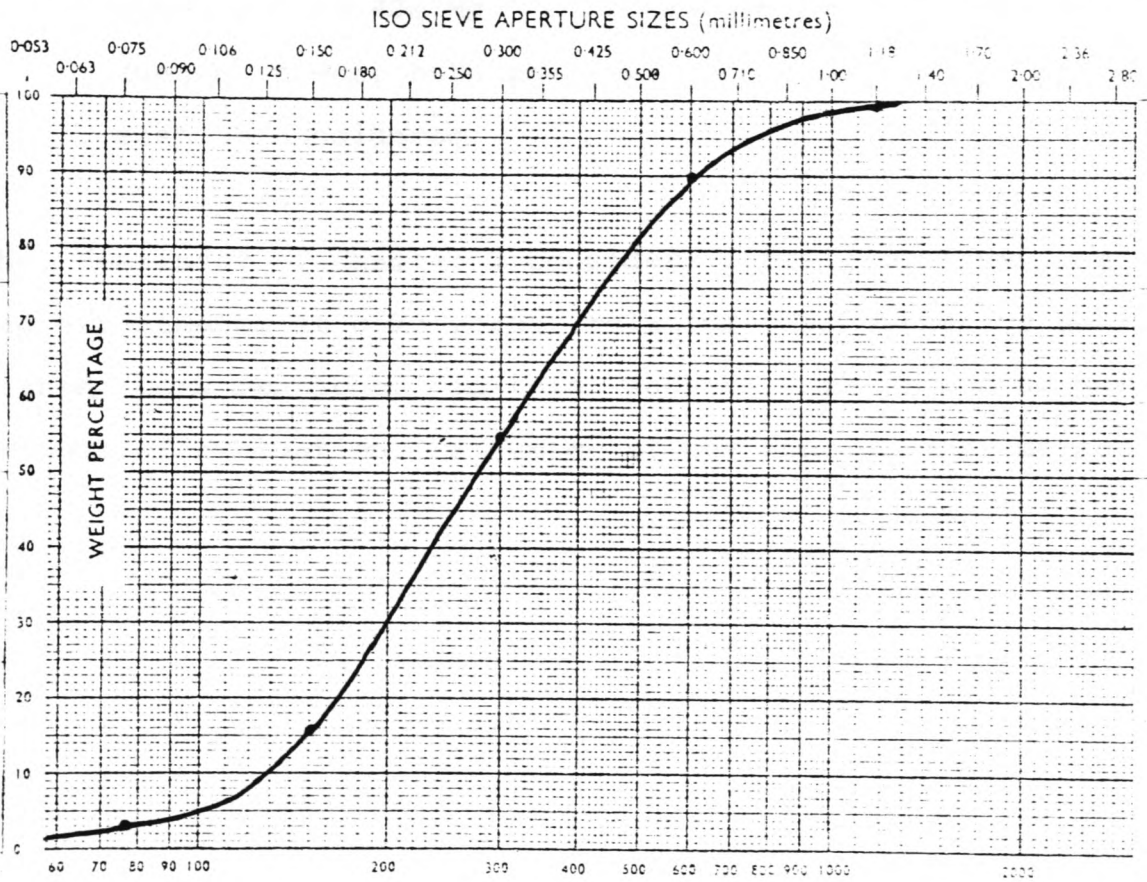


Fig. 31
Particle Size Analysis
Fullerton Data

Carbonisation Research Association, the National Coal Board, and major coke oven manufacturers. Their recommendations included the use of baffle-type arrestors.

3.1.15 Data by Murphy on the water gas reaction during coke quenching was reported (48) in 1982. In the sealed-quench system described, water gas production was noted as $36-43\text{m}^3\text{Mg}^{-1}$ of coke quenched. Thus in the quench tower, both chemical and physical processes must be considered.

The remainder of Chapter 3 considers certain observations, and experiments at coke works, relating them either to published work mentioned in this section, or proposing new methods of evaluation. A number of new conclusions emerge.

3.2 ELUTRIATION OF PARTICULATE MATTER FROM QUENCH TOWERS

3.2.1 ARRESTMENT EFFICIENCY VERSUS PARTICLE SIZE

The overall efficiency of high wooden louvres was reported by Jackson and Waple(19) as 50%. From the published data, estimates of arrestment efficiency in relation to particle size have been made.

The reported sizings are shown in Fig.29. Smoothed values can be interpolated for discrete size intervals over the range 0-1000 μ m, although it should be noted that data on sizes over 600 μ m are based on extrapolation. The calculated arrestment efficiencies are shown in Fig.32. They range from over 80% (possibly as high as 100% for the coarsest particles) down to 40% and less for particles below 200 μ m.

3.2.2 EFFECT OF CARBONISATION TEMPERATURE ON QUENCH TOWER EMISSIONS

Blast furnace coke is carbonised typically for 18h at heating flue temperatures of 1520-1620K, and foundry coke for more than 24h at 1320-1370K. Two references indicate a variation in quench tower emissions with carbonisation temperature:-

- (a) Investigations (13) in 1959 compared the material collected in deposit gauges near a blast furnace coke works quench tower (flue temps. 1570-1620K) and near a foundry coke works quench tower (flue temps.1320-1370K). The results indicated that

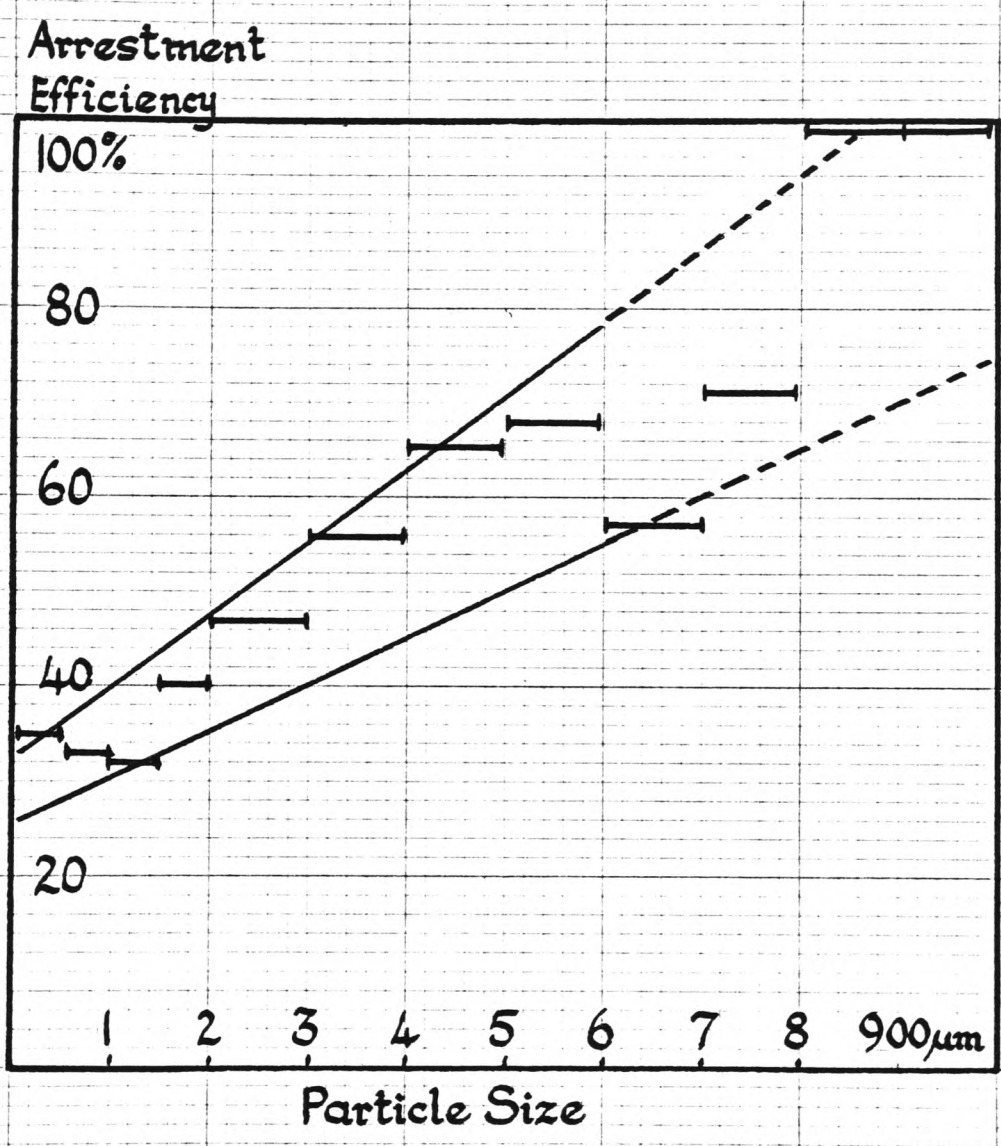


Fig. 32
Arrestment Efficiency vs. Particle Size
Jackson & Waple (19)

deposition around the latter was only 40% of that around the former.

- (b) Investigations(19) in 1980 indicated emissions of 107g Mg^{-1} for a carbonisation period of 35.5h, compared to 535g Mg^{-1} for a period of 19.5h, where the heating flue temperatures were 100°C higher.

To verify these results, further experiments have been done:-

- (c) In Chapter 2, examples are given which show that around B.S.C. Llanwern the more distant gauges were affected beneficially as a result of grit arrestor uprating, but were unaffected by improvements in carbonisation control. However, in May 1983, an additional battery of 4m ovens was commissioned, but total production remained steady. The carbonisation temperature was reduced, causing a further beneficial step change on the Deposition CuSum chart. (See Fig.16)
- (d) A deposit gauge is located 2km from a foundry coke works and 3km from a blast furnace coke works. In mid-1982, arrestment was uprated at the blast furnace coke works and the Deposition CuSum chart for this gauge showed a marked reduction. However, before the full step change was completed, some ovens were taken out of service for rebuilds at the foundry coke works, but total production remained steady. The higher carbonisation temperature that resulted caused

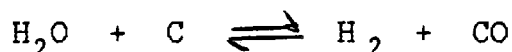
an adverse step change, as shown in Fig. 33. This chart is considered further in section 3.3.2.4. The residual S.D. of 25mg m⁻²d was based on 8 months of results after the modifications at the blast furnace coke works.

- (e) A further example of this adverse effect is described in section 3.3.2.2. at the British Benzole Coke Works, and is shown in Fig.35.

These examples confirm that emissions from quench towers increase with increase in carbonisation temperature and vice versa. The majority of the fine particles remaining in the coke on discharge from the ovens would be removed by the intense thermal bouyancy. It is therefore probable that the particulate matter emitted from quench towers arises from subsequent chemical and/or physical reactions.

3.2.3 THE WATER GAS REACTION DURING COKE QUENCHING

The reaction between water and coke at 1370-1470K produces water gas, and conditions at peak emission rates in a quench tower can be likened to those in the reduction zone in a producer gas generator(22). The water gas reaction:-



causes an increase in the gas volume within the quench tower. The reaction absorbs heat, and hence the coke temperature will fall rapidly. Below 1170K, the reaction rate is negligible.

- (a) Arrestment modifications at Blast Furnace Coke Works
- (b) Change In Carbonisation Regime At Foundry Coke Works

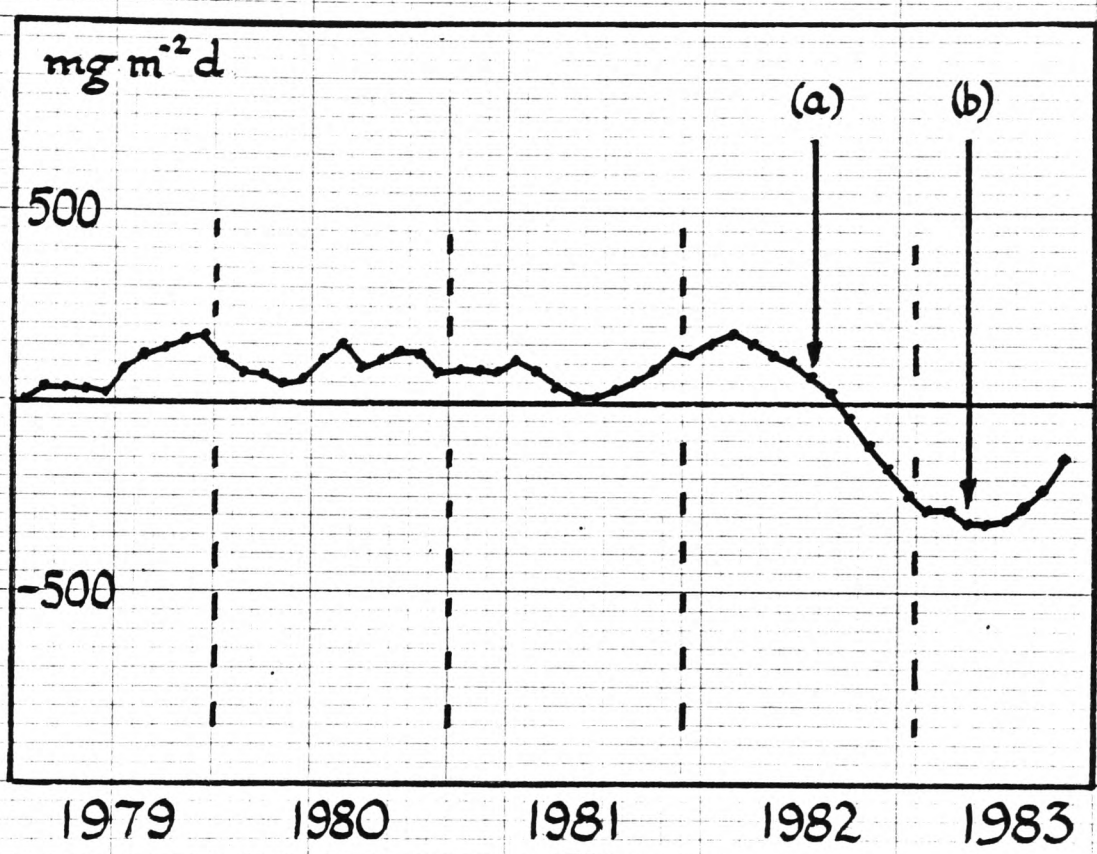


Fig.33

Deposition CuSum Chart
 For Gauge sited 3000m.
 From Blast Furnace Coke Works

Using a sealed-quench system, Murphy(48) stated that "during the first 30s of the quench, only water gas is produced", but the composition changes rapidly, and is 100% steam after 40s. In a quench tower with arrestment, equivalent conditions will be found at peak emission rates, during quenching.

Water gas production is given as circa $40\text{m}^3 \text{ Mg}^{-1}$ of coke quenched. With 4m ovens, total water gas production would thus be in the order of 520m per quench, and this would probably all be emitted within the first minute. It is evident that the additional volume of gas produced by the water gas reaction will be a factor in the rapid initial rise in emission velocity noted by Jackson and Waple(19).

Production of water gas will lead to loss of fixed carbon, and the release of its associated ash. Based on South Wales coke with 87% fixed carbon and 10% ash (dry wt. basis), calculations can be made on the loss of fixed carbon using typical gas composition and gas density(24) for water gas. These show that the loss of ash associated with the fixed carbon consumed would equal 636g Mg^{-1} of coke quenched:-

Gas Composition	CO 41% CO ₂ 4.7% CH ₄ 0.8%
Carbon Content	19.45%
Density	0.711kg m^{-3}
Thus 40m^3 weighs	28.44kg

Thus carbon loss	5.53kg Mg ⁻¹
Coke equivalent	6.36kg Mg ⁻¹
Associated ash	0.636kg Mg ⁻¹ of coke quenched

These calculations indicate a potential release rate for particulate mineral matter from the ash similar to the emission rates reported from open towers at blast furnace coke works. The potential for release must be considered high because of the fine particle size of the mineral matter in the coke. In addition, the large reduction in particulate emission from quench towers at foundry coke works could be explained by the reduced rate of the water gas reaction at the discharge temperature of foundry coke.

3.2.4 DISTRIBUTION OF PARTICULATE MATTER IN QUENCH TOWERS

During quenching, particulate matter covering a wide range of particle sizes is released. The coarser particles gravitate to the settling ponds, and the finer particles are emitted. Data on the distribution between these two routes have not been published. No comparative studies have been made simultaneously at the same site, but estimates can be made from separate studies:-

(a) FOUNDRY COKE WORKS

Studies(13) in 1959 indicated that settling pond coke breeze amounted to 2.2kg Mg⁻¹ at a carbonisation period of 28.5h.

Studies(19) in 1960 indicated that emissions were 107g Mg^{-1} at a carbonisation period of 35.5h.

(b) BLAST FURNACE COKE WORKS

Studies(14) in 1959 indicated that settling pond coke breeze amounted to 5.06kg Mg^{-1} at a carbonisation period of 18.5h.

Various researches (12,19,26,27) have quoted values for emission rates which depend on emission velocities. A typical rate for the tower under study would be circa 500g Mg^{-1} .

Thus with both types of coke, the major exit route for particulate matter is via the settling ponds, and increased solids recovery due to uprated grit arrestment will be relatively minor.

3.2.5 EFFECT OF GRIT ARRESTORS IN PARALLEL-SIDED QUENCH TOWERS

This is illustrated by the work of Jackson and Waple (19). The tower was 13.7m long, divided vertically into 3 separate bays of approx. equal size. With the open tower, entering the car fully into the tower before quenching gave the greatest emissions from bay B. There is little lateral dispersion in an open tower, but installation of arrestors redistributed more of the emissions into the end bays. Estimated gas velocities are given in Table 16:-

EXIT VELOCITIES (m s^{-1})						
TIME INTO QUENCH(s)	OPEN TOWER			WITH ARRESTMENT		
	BAY A	BAY B	BAY C	BAY A	BAY B	BAY C
20	1.82	5.30	2.12	3.78	3.97	3.18
30	1.82	5.30	2.12	2.78	3.97	3.45
60	1.33	3.98	1.33	1.13	2.98	1.99
90	0.73	3.25	0.73	0.53	2.98	1.33
120	0.73	2.65	0.73	1.19	2.19	1.79
150	0.73	1.72	0.73	0.80	1.86	1.72
180	0.73	1.33	0.73	0.86	1.46	1.33

Table 16

GAS VELOCITIES WITH AND WITHOUT ARRESTMENT (19)

An important function of grit arrestors is thus to make more effective use of the full plan area of the tower beneath the arrestors, and hence to reduce peak exit velocities.

By reducing peak exit velocities, introduction of grit arrestors would also reduce the maximum size of particle elutriated. This would reduce the amount of undissolved solids emitted, in addition to any mechanical capture effect, and the major effect would be noted in nearby deposit gauges. The change in particle size distribution of the emissions with and without arrestment, as shown in Fig. 29 for Jackson and Waple data, conforms with such a conclusion.

3.2.6 THE EFFECT OF EFFLUX VELOCITY ON DOWNWASH FROM QUENCH TOWERS

An important method of reducing emissions from quench towers is to design for an upward velocity in the spray area which is as low as reasonably practicable. However, low efflux velocities can cause downwash. On the lee side of a tower there exists a low pressure zone. If the efflux velocity is not adequate for the plume to break clear, it can be drawn down into this zone for a considerable distance.

In practice, by analogy with chimney emissions, to design for an efflux velocity adequate to overcome downdraught will be more important than increasing the height of discharge.

Wind tunnel tests of chimney emissions have shown that downwash does not occur when the efflux velocity exceeds 1.5 times the wind velocity, and that when the two are similar, downwash will nearly always occur (14). In general, with parallel-sided quench towers, efflux velocities seldom exceed 6 m s^{-1} , and hence they will be subject to frequent downwash.

Efforts to minimise this problem led to the development of tapered towers. These are taller, in order to generate the greater draught needed, but unfortunately, this leads to elutriation of coarser particles

and can cause greater nuisance. Jackson and Waple reported (19) that deposition from tapered towers was in a more closely-defined band than from parallel-sided towers, indicating that the former were possibly being less affected by downwash.

However, a satisfactory compromise is possible with tapered towers, in which the plan area beneath efficient grit arrestors is made large. Afterwards the tapered construction will be helpful in minimising the effect of downwash by giving higher efflux velocities.

3.3 DEPOSITION OF UNDISSOLVED SOLIDS FROM QUENCH TOWER EMISSIONS

3.3.1 THE PRINCIPAL EXPERIMENT AT UPRATING

The principal experiment was carried out at the coke oven plants at B.S.C. Llanwern. This works has 4 batteries of 4m ovens, served by two tapered quench towers, and one battery of 6m ovens, served by a separate, larger, tapered tower. Although differing in scale, the essential features of the grit arrestment system are identical, and are as described in 3.1.9.

The high pressure drop across this configuration might appear to be higher than for 70° louvres, and hence it would be expected that the arrestment efficiency would be higher. However, examination of Fig.34 shows some problem areas, which are circled, with gaps in the arrestment surface. One was close to the point of steam evolution, while the others were at the end of the natural path for the steam plume at the top of both sides of the arrestor. The gaps were present for the full width of each tower. The exit gases would be expected to follow preferentially the path of lowest pressure drop, and the concentration of particulate matter in the exit gases would be far higher than planned.

A detailed inspection of the larger quench tower in August 1980 revealed the need for some remedial work.

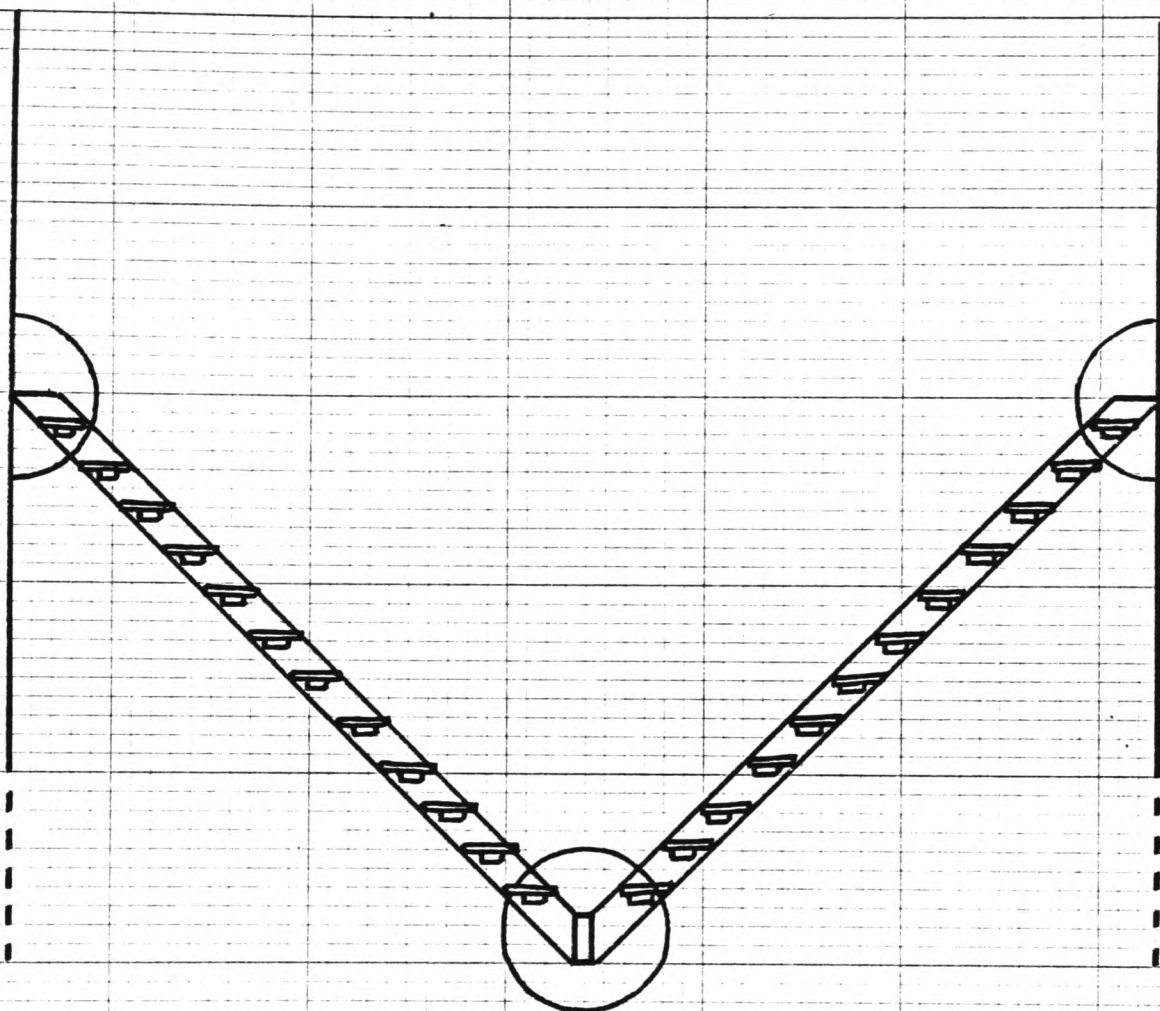


Fig. 34
Grit Arrestment System
Showing Points
Of Potential Emission

The opportunity was taken to refurbish the arrestors, and design changes were introduced to ensure that there was a continuous arrestment surface. The support structure was also strengthened, because it would be subjected to higher pressure and temperature.

The results of this experiment have been discussed in Chapter 2. The following salient points emerge:

- (a) The modifications caused reductions in the levels of deposited matter in all surrounding gauges.
- (b) The reductions were generally substantial, and in two cases exceeded 50%. Both of these gauges were more than 2km from the quench towers.
- (c) The end of the step change was usually quite distinct. This was particularly the case with the Nash gauge where the Deposition CuSum chart remained essentially horizontal.
- (d) Statistical tests have been applied to these results, as described in Chapter 2, and the results have been shown to be highly significant.
- (e) The residual S.D. at the nearby gauges, after up-rating the grit arrestment, indicated another source of severe contamination. This was shown later to be due to emissions from coke oven discharges, considered separately in Chapter 4.

Further experiments were then arranged at other coke works to confirm these findings, both for nearby gauges, and for more distant gauges.

3.3.2 CONFIRMATORY EXPERIMENTS AT NEARBY GAUGES

In view of the reduction in exit velocity on installation of grit arrestors, it can be postulated that this would result in reduced emission of the coarser solids, which deposit close to the quench tower. Therefore, experiments were designed for works where deposit gauges were sited relatively close to the tower. The following examples relate to gauges within 200m of a quench tower.

3.3.2.1 THE EFFECT OF BLOCKAGES IN GRIT ARRESTORS

An experiment was carried out at a works making foundry coke. It has been reported (19) that the quench tower emissions from coke made with extended carbonisation periods were less than with blast furnace coke, so this was considered a very stringent test.

The works used 4m ovens, and the parallel-sided quench tower had a single layer of inclined louvres at 70° in the high position, with a pitch of 58mm. No upper cleaning sprays were installed. Detailed inspection showed that fine coke breeze build-up was extensive in each of the three bays of the tower. The louvres were thoroughly hosed down in September 1980, thereby reducing the gas velocity through the arrestment system, and procedures were introduced to ensure they were subsequently cleaned regularly.

No other modifications were made, and hence this experiment shows the effect of operating the arrestment system at its design gas velocity, rather than at a higher velocity due to fouling.

The Deposition CuSum chart is shown in Fig.35. (Data collection only began in 1979.) It should be noted that the step change did not run its full 12 months, due to a change in the operating regime after 6 months, involving the closure of certain ovens, and a higher carbonisation temperature for those remaining. In the absence of this change the step change would probably have been much greater. (The data for this evaluation were kindly supplied by Rhymney Valley District Council.)

The magnitude of the partial step change was in the order of $900\text{mg m}^{-2}\text{d}$. The short-term residual S.D. following the cleaning operation was approximately $40\text{mg m}^{-2}\text{d}$. No other, more distant, gauges were available to give background deposition data for this area, but even using the value of $40\text{mg m}^{-2}\text{d}$, it can be seen that the SVD will be greater than 10 times the residual S.D. of the partial step change, and hence the improvement is highly significant.

It is clear therefore, that arrestment systems with no overlap between louvres are extremely sensitive to gas velocity, and must be cleaned regularly.

(a) Coke Fines Build-Up Washed Away
(b) Change in Carbonisation Regime

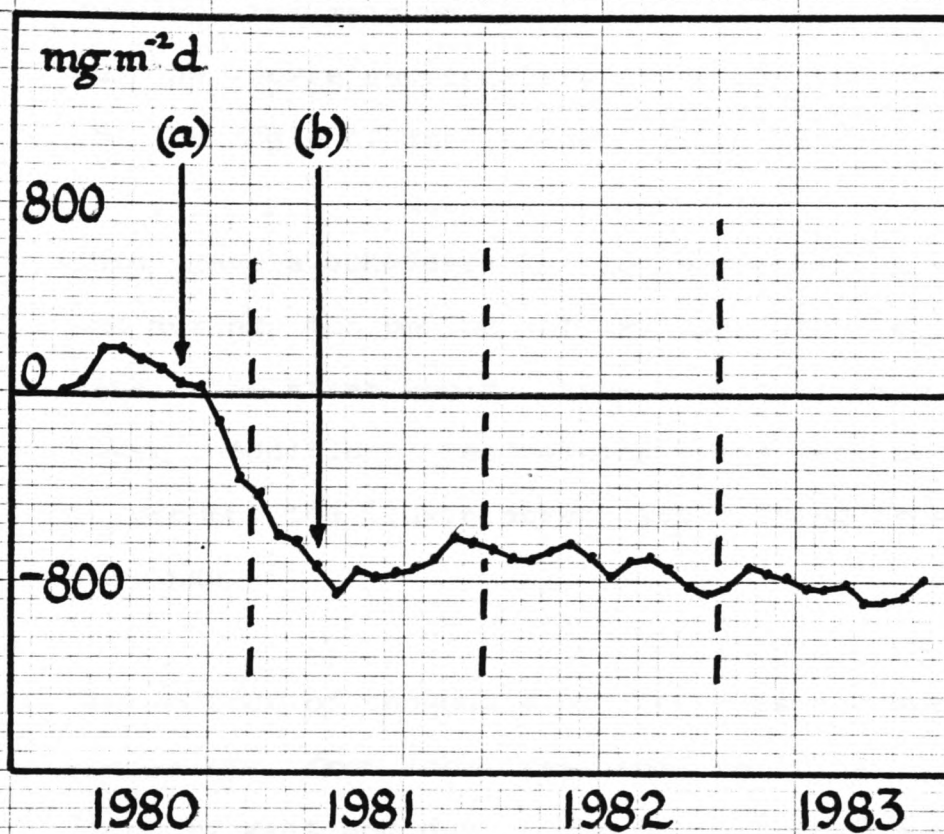


Fig. 35

Deposition CuSum Chart
For Gauge Sited Near
To Foundry Coke Works

3.3.2.2 THE EFFECT OF UPDATING GRIT ARRESTMENT

The opportunity to uprate an arrestment system based on the Portchmouth(7) design was taken following complaints from householders living less than 200m from a quench tower serving 4m ovens at a blast furnace coke works. To achieve complete overlap, two main changes were made:-

- (a) The louvre sections were enlarged to 100x12.5mm
- (b) The angle of inclination was reduced to 45°.

This gave a considerably increased pressure drop, and during the period of maximum steam evolution rate, the steam would issue from the base of the tower. Additional restraining beams were necessary to prevent the louvre assemblies lifting from their settings.

The effect of the modifications was to remove all complaints from local residents relating to deposition of grit and dust. The Deposition CuSum chart for a gauge sited within 200m of the quench tower is shown in Fig.36. Following the changes, the mean deposition values fell from 225 to 100mg m⁻²d. Since the works concerned is at the edge of an industrial estate, it would be expected that background deposition values would be above 50mg m⁻²d, so it is probable that the emissions from the tower had made up the major part of the total deposits.

The step change shown on Fig.36, which takes into account a previous trend line on the CuSum chart prior to the modification, was circa $1100\text{mg m}^{-2}\text{d}$. (The trend line was calculated using the system of least squares based on results from July 1980 to June 1982.) The residual S.D. for this gauge after the modifications was circa $100\text{mg m}^{-2}\text{d}$. There are five gauges monitoring this works, and for three of these the residual S.D. was circa $40\text{--}50\text{mg m}^{-2}\text{d}$ over the same period. The SVD is seen to be greater than ten times the background residual S.D., and so the reduction is highly significant.

It is considered that the two examples quoted confirm beyond reasonable doubt that changes to grit arrestment systems cause changes in deposition values in gauges close to the towers, which are highly significant. Improved arrestment also brings a marked reduction in variance of the deposition data, indicating that ineffective arrestment had previously been an important cause in the variability in monthly data.

3.3.3 CONFIRMATORY EXPERIMENTS AT DISTANT GAUGES

It was shown in 3.3.2.2 that the reduction in deposition at a gauge sited 150m from a quench tower at a blast furnace coke works, after grit arrestment modifications, had been highly significant.

(a) Grit Arrestment Modification

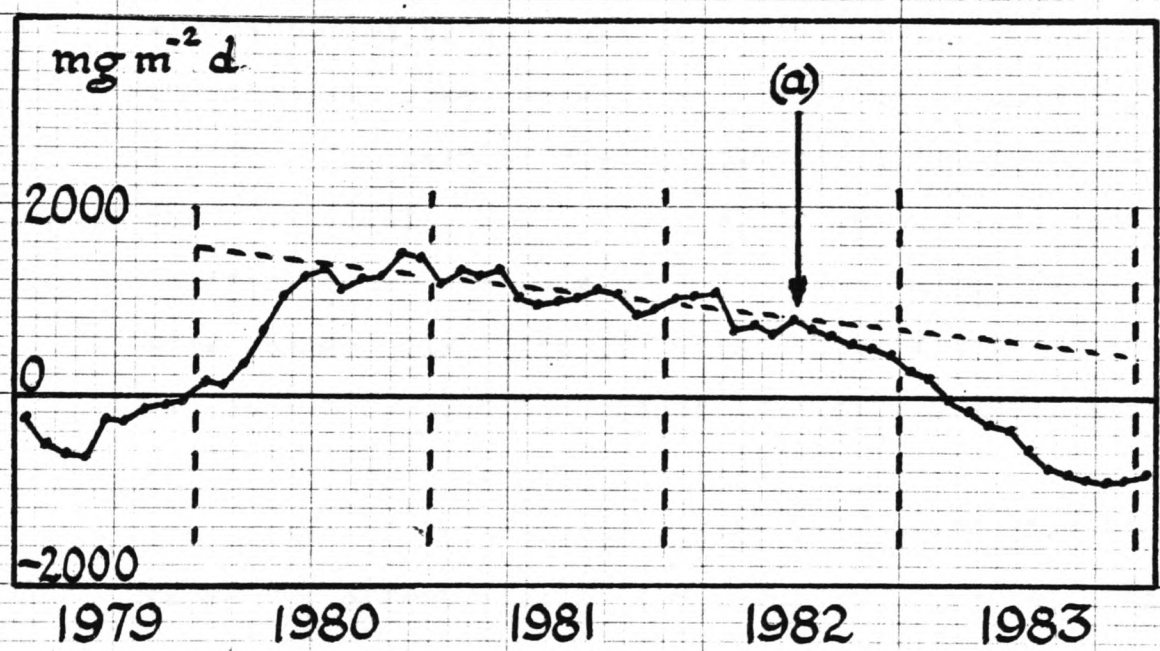


Fig. 36
Deposition CuSum Chart
For Gauge Sited Near
To Blast Furnace Coke Works

Deposition at a gauge 3km distance (sited to monitor a foundry coke works a further 2km distance) also reduced following the above modification. The Deposition CuSum chart for this gauge appears as Fig.33 in section 3.2.2. It had not departed greatly from the horizontal over the previous 3-4 years, but fell sharply afterwards. No changes had been made at the foundry coke works at that time. The step change was, however, incomplete, when the gauge was adversely affected by a change in carbonisation regime at the foundry coke works, as described in section 3.2.2. The partial step change was $400\text{mg m}^{-2}\text{d}$, and the residual S.D. following the arrestment modifications was $25\text{mg m}^{-2}\text{d}$. Based on the partial step change only, the SVD is thus 8 times the residual S.D., and the change is highly significant.

The shape of this CuSum chart indicates that the gauge was affected from two sources, one at 2km distance, and one at 3km.

Confirmation of the adverse effect of the change in the carbonisation regime is found in Fig.37, which is a Deposition CuSum chart for a gauge sited in the foundry coke works. This shows that gauges 2km apart were affected by the same changes. The size of the step change for this gauge is also highly significant, based on the background residual S.D.

- (a) Grit Arrestment Modification
(b) Change in Carbonisation Regime

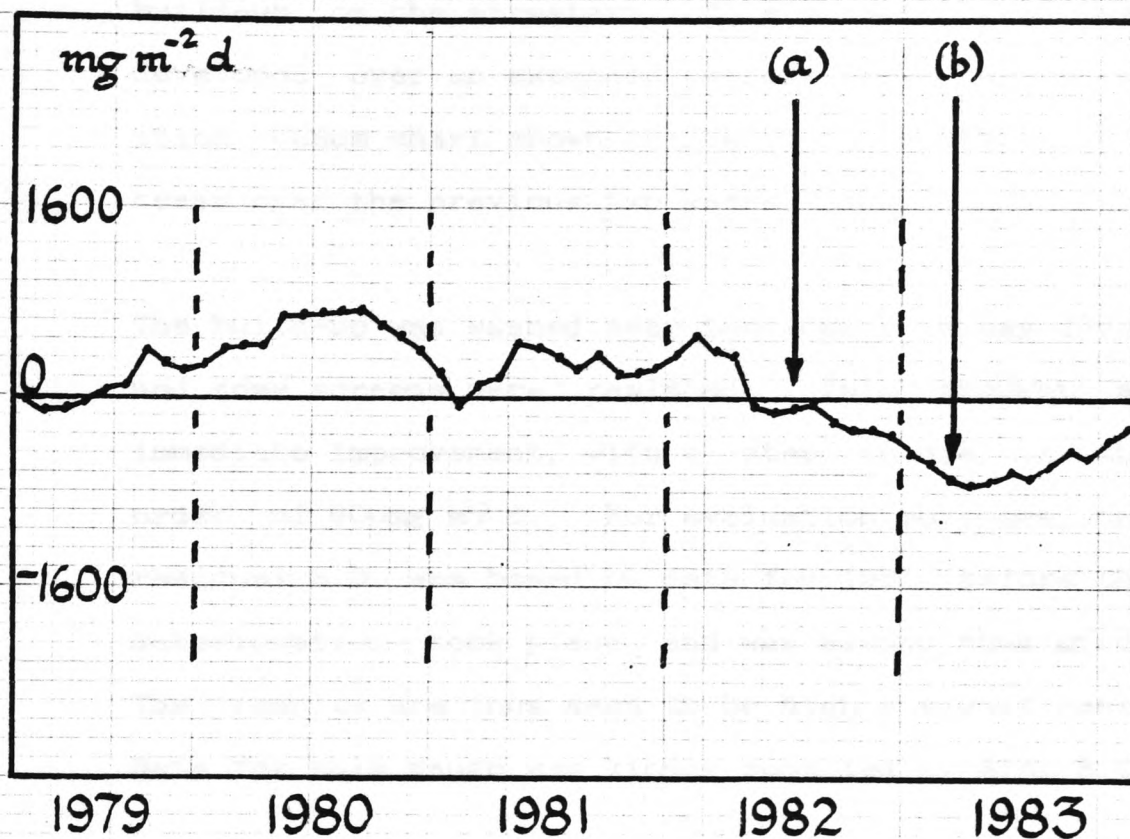


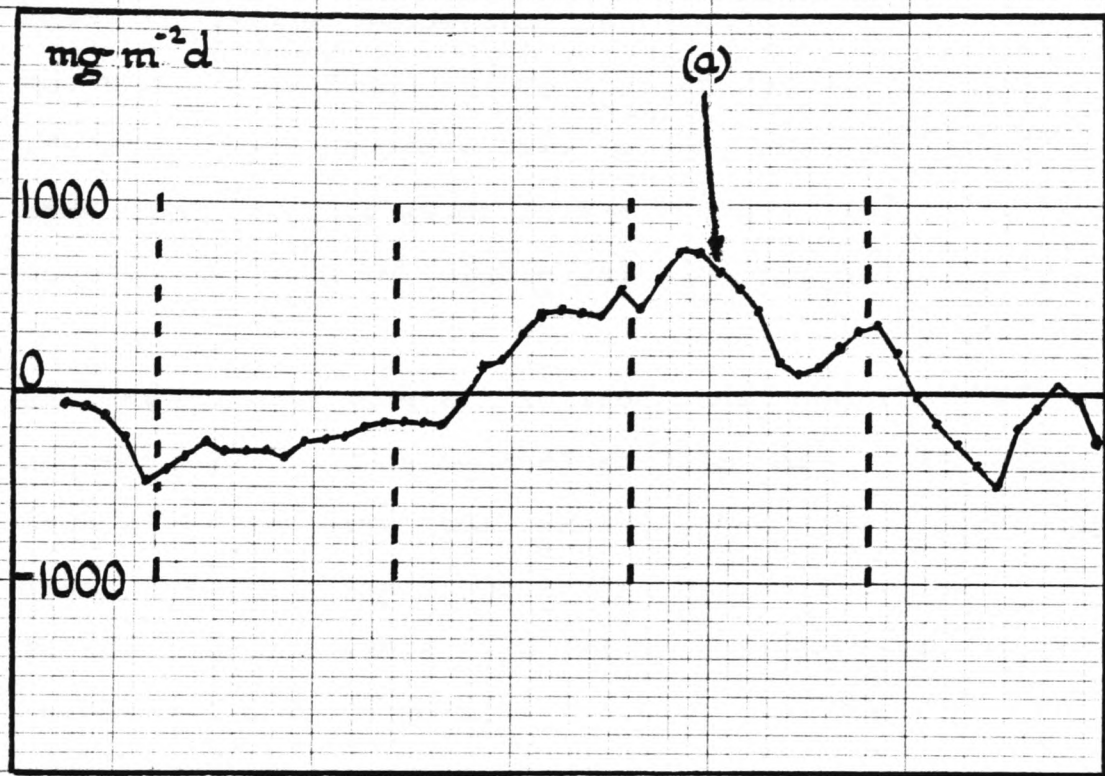
Fig. 37
Deposition CuSum Chart
For Gauge Sited In
Foundry Coke Works

The final confirmatory experiment concerned a quench tower fitted with wedge-wire screens as grit arrestors, serving 4m ovens making foundry coke. The screens were designed to be continuously irrigated. Inspection revealed that the irrigation sprays were largely inoperative, which had caused a considerable build-up on the arrestors. This situation may have developed over an extended period, since the Deposition CuSum chart shown in Fig.38 had a steady increase over the previous two years.

The build-up was washed away thoroughly in May 1983, and some screens were replaced. This brought an immediate improvement, with a step change in the order of $900\text{mg m}^{-2}\text{ d}$. For evaluation purposes, the residual S.D. was based on data for 1981, before the deterioration took place, and was around $50\text{mg m}^{-2}\text{ d}$. The results are thus seen to be highly significant. Data for this gauge was kindly supplied by Afan B.C.

These results are considered as confirmation of the long-distance dispersion of emissions of undissolved solids from quench tower.

(a) Grit Arrestment Repair



1981 1982 1983 1984

Fig. 38

Deposition CuSum Chart
For Gauge Sited
2 km.
From Foundry Coke Works

3.4 THE EFFECT OF UPGRATING GRIT ARRESTMENT ON DEPOSITION OF DISSOLVED SOLIDS

The work by Chilton(5) was intended mainly to reduce the emission of water droplets. Some investigators(27) have surmised that a reduction in water droplet emission should lead to reduced deposition of soluble salts, but no references could be found in the literature to experiments specifically made to prove this point. Evaluations have thus been made in this study to see if improved grit arrestment caused reduction in soluble salt deposition.

One report was made(27) in 1968 that the dissolved solids content had been calculated at 350g Mg^{-1} of coke quenched. This will vary with the hardness of the water supply. Often, waste process water or boiler blow-down is used. The following example is based on average fresh water quality at a U.K. coke works:-

Average Total Hardness	=	750-1500ppm as CaCO_3
Water Evaporation Rate	=	450-500kg Mg^{-1} coke
Total Soluble Salt Content	=	315-750g Mg^{-1} coke
Coke Production Rate	=	2500Mg d^{-1}
Daily Soluble Salt Content	=	788-1875kg
Average Deposition Rate (over area of 2.5km ² only)	=	315-750mg m^{-2}d

These calculations show that high deposition rates would be found if all the soluble salts were emitted, and deposited

in an area of say 2.5km^2 (1 square mile) around a tower. Such high figures have not been noted in past data, which indicates in general that:-

- (a) Quenching is not a major source of soluble salts, or
- (b) Any emissions are dispersed over a much wider area.

The average values recorded(35) around B.S.C. Llanwern prior to these experiments were typically in the range of $25\text{-}50\text{mg m}^{-2}\text{ d}$, and were circa 12-25% of the values for undissolved solids.

Several experiments have been carried out in South Wales as part of this study, to determine the effect of grit arrestment on deposition of dissolved solids, to see if the postulated reduction could be detected. One such was at a foundry coke works which had been operating at a modest rate, without effective grit arrestment. In November 1982, louvres of the Portsmouth(7) type were installed having an inclination of 70° . This brought an immediate increase in the levels of dissolved solids detected in the nearest deposit gauge, about 150m from the tower, on sharply rising ground. The Deposition CuSum chart is shown in Fig.39. For two years before the modification, the average value had been $90\text{mg m}^{-2}\text{ d}$, while over the three months following, it rose to $390\text{mg m}^{-2}\text{ d}$. The residual S.D. based on a reference period before the change was circa $70\text{mg m}^{-2}\text{ d}$.

The abrupt increase was halted when upper irrigation sprays were installed in February 1983, and the chart resumed its

(a) Improved Grit Arrestment
(b) Installed Upper Sprays

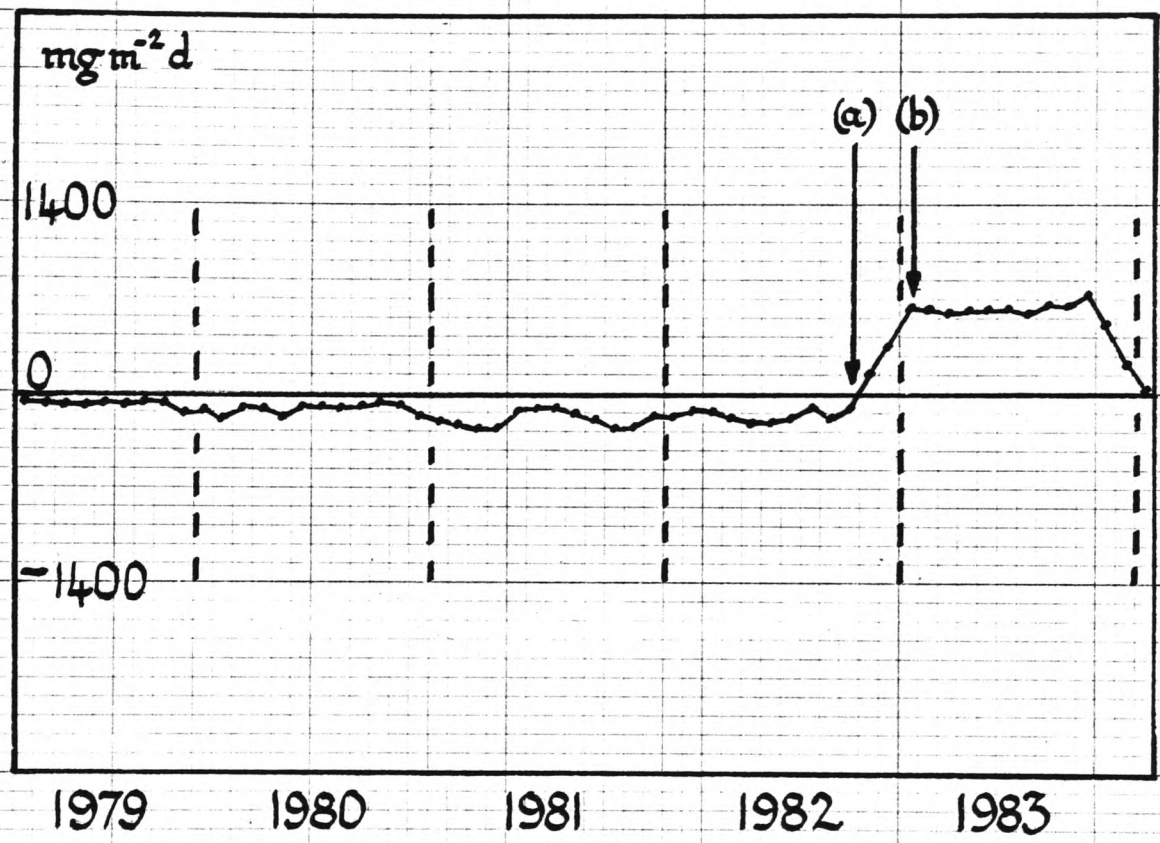


Fig. 39
Deposition CuSum Chart
For Dissolved Solids
Near To Foundry Coke Works

horizontal path, until falling abruptly again in November 1983. Prior to this work, it had been assumed that the sole function of upper sprays was to stop accumulation of coke breeze on the louvres. It now appears the sprays may have a more important function in abating emissions of soluble salts. It can be seen from Fig.39 that the step change after only 3 months was circa 10 times the residual S.D., and hence this effect is highly significant.

For confirmation of this effect, similar charts were made for gauges at another coke works, 5km to the East. The chart for the nearest gauge, circa 4km from the above quench tower, is given in Fig.40. The adverse effect of the arrestment changes, and the beneficial effect of the upper sprays are evident. However, the chart already had an upward trend, which persisted after installing the sprays. This was considered the result of the other arrestment modifications at the blast furnace coke works a further 5km to the East, described in section 3.3.2.2. It is more difficult to evaluate the results due to this dual effect. However, it can be seen that the step change during the 3 months in question was 10 times the residual S.D. and that about 30% of that would have been due to the previous trend. The change is thus highly significant.

As a final check in this location, another chart was made for the gauge sited within 200m of the blast furnace coke works (section 3.3.2.2) where the quench tower had been modified in mid-1982. The chart is given in Fig.41, and

- (a) Improved Grit Arrestment 5 km. West
- (b) Improved Grit Arrestment 4 km. East
- (c) Installed Upper Sprays 4 km. East

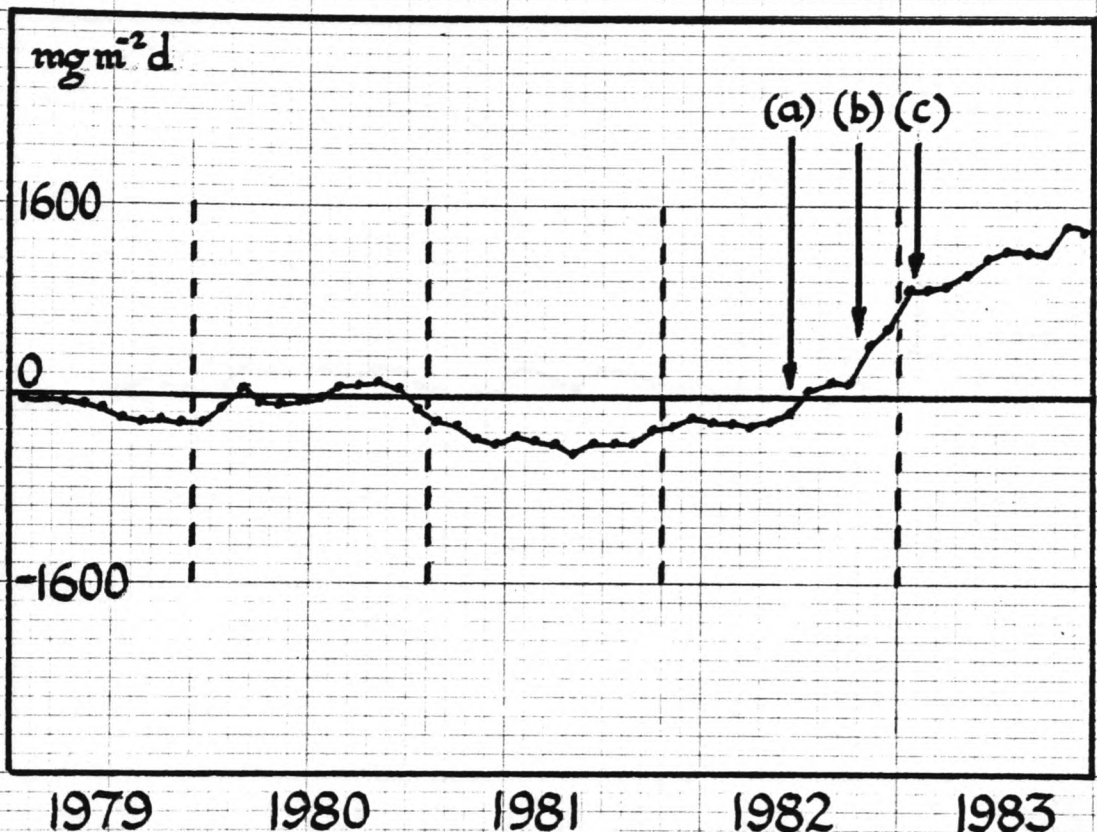


Fig. 40
Deposition CuSum Chart
For Dissolved Solids
Distant Gauge

- (a) Grit Arrestment Mods. At Nearby Tower
- (b) Grit Arrestment Mods. 10km. West
- (c) Upper Sprays Installed 10 km. West
- (d) Grit Arrestment Mods. 5km. West

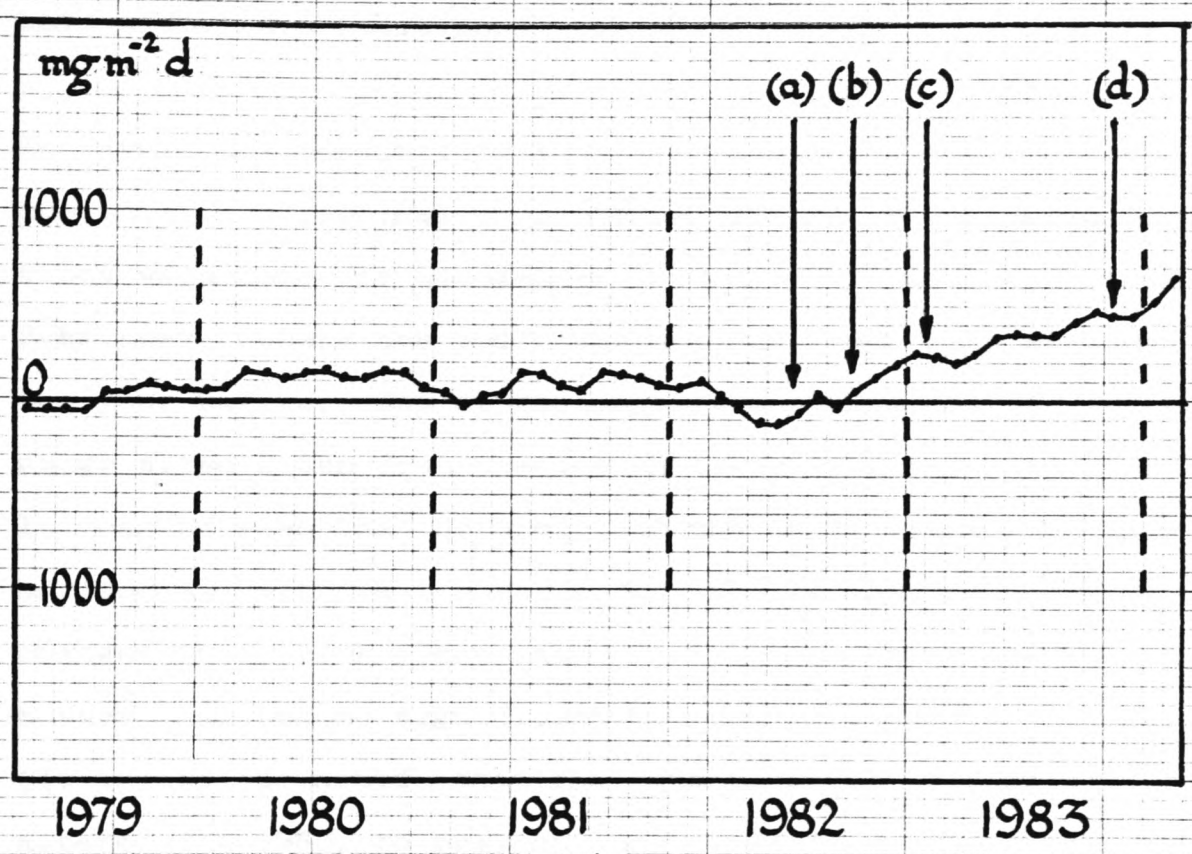


Fig. 41
Deposition CuSum Chart
For Dissolved Solids
Near Blast Furnace Coke Works

indicates an increase in dissolved solids over a period of about 18 months. This tower had previously been fitted with upper sprays, and so the change in louvre angle from 70° to 45° would give a more modest increase in emissions of dissolved solids. The significant points are noted on Fig.41, and it can be seen that changes at distant gauges have affected deposition of dissolved solids at this gauge.

To avoid any possibility that the increase could have been due to a geographical or seasonal freak, similar evaluations were done for the gauges around B.S.C. Llanwern, some 30km away, where the modifications had been made at least one year before. One of the Deposition CuSum charts, for a gauge sited 2.8km from the quench tower is given in Fig.42. It can be seen that before 1980 the chart was essentially horizontal, with a low value for the residual S.D. Major changes then took place, and it is clear that the quench towers had become significant sources of dissolved solids. (It should be noted that the quench water flowsheet was altered in 1980, to prevent any purge from the system to drain. This ensured that all water left the system via the steam plume. The periods before and after the change are thus not strictly comparable, but the results nevertheless confirm the long-distance dispersion of dissolved solids from quench towers.)

There were no upper cleaning sprays in the quench towers at the time of these evaluations. In 1984, an experiment was devised which involved the installation of upper cleaning

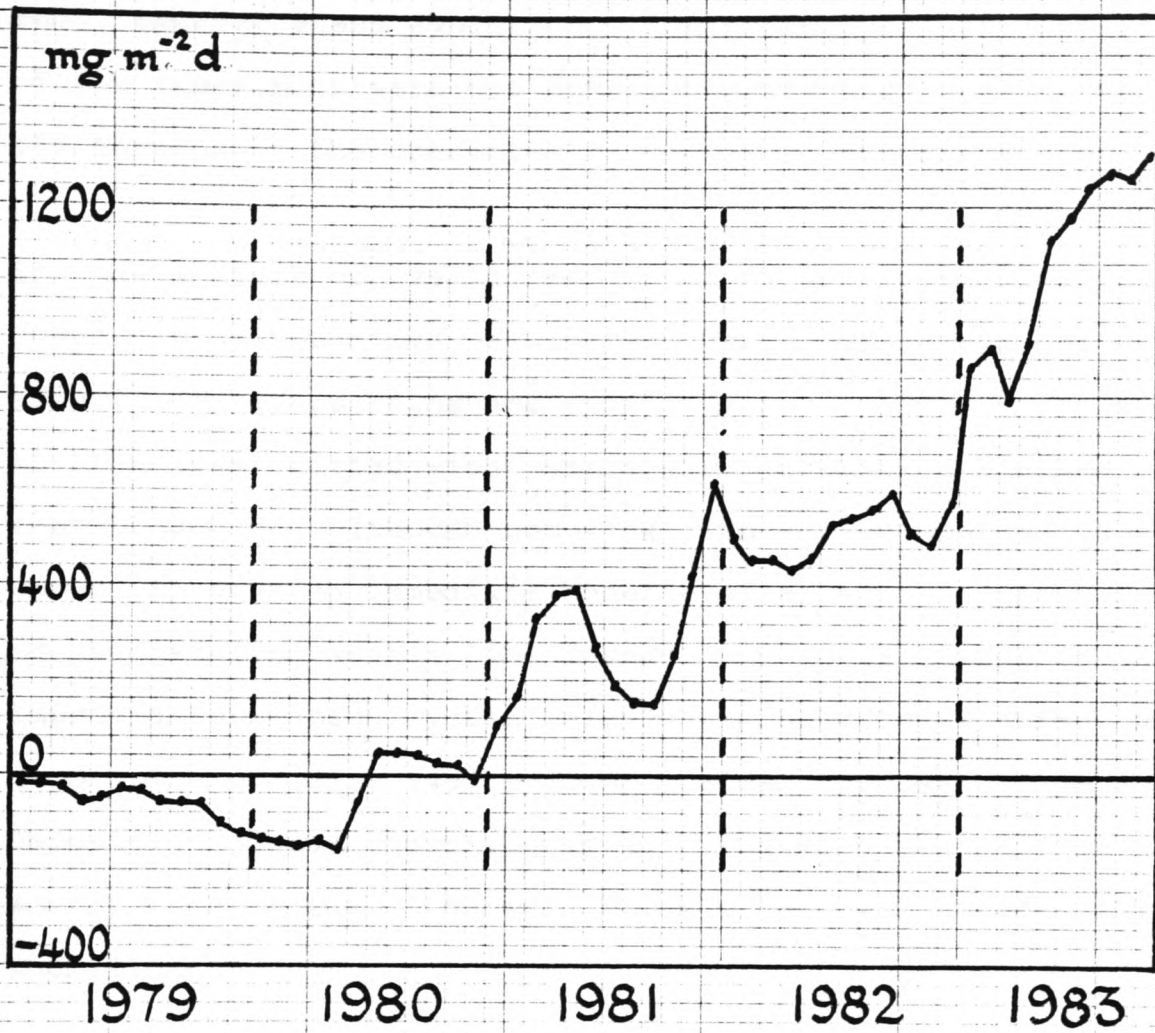


Fig. 42
Deposition CuSum Chart
For Dissolved Solids
2.8 km From
B.S.C. Llanwern

sprays in the tower serving the 6m ovens, at an installed cost approaching £30,000. These were designed to operate for only one minute during each quench, for the period of most intense steam evolution. Unfortunately, the results of the experiment were not determined, as the local authority terminated the operation of the local deposit gauges.

In the absence of valid results from this planned experiment, an alternative evaluation was carried out on the effect of refurbishing and expanding the irrigation system at the tower fitted with wedge-wire screens, described in section 3.2.3. Although removing the build-up had been shown to have an immediate beneficial effect on deposition of undissolved solids, the design and installation of the improved irrigation system delayed the beneficial effect on deposition of dissolved solids, as can be seen from the Deposition CuSum chart in Fig.43. The step change over 12 months from August 1983 was $950\text{mg m}^{-2}\text{d}$, which was highly significant.

- (a) Coke breeze build-up removed
- (b) Irrigation sprays refurbished

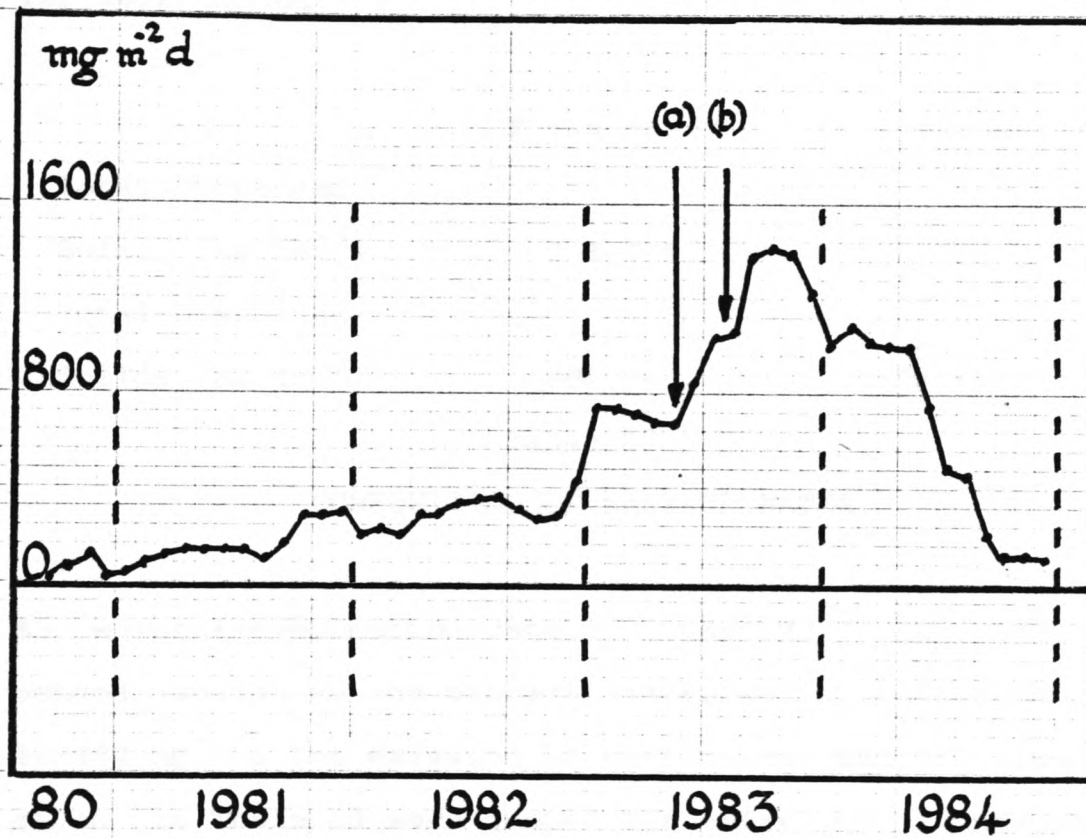


Fig. 43

Deposition CuSumChart
 Showing Effect Of Irrigation Sprays
 On Dissolved Solids

3.5 THE EFFECT OF QUENCH WATER QUALITY ON EMISSIONS FROM QUENCH TOWERS

Some results were reported in 1981 in the U.S.A.(47) based on measuring particulate emissions from quench towers using "clean" and "dirty" make-up water, classified according to the dissolved solids content. The following water qualities were quoted:-

	Fresh Water	Process Water
Total Suspended		
Solids (mg dm^{-3})	3.3-5.5	75-104
Total Dissolved		
Solids (mg dm^{-3})	390-506	1627-1904

Table 17

COMPOSITION OF MAKE-UP WATER

At a water evaporation rate of $0.45\text{m}^3 \text{ Mg}^{-1}$, the total suspended solids in the process water would contribute circa $35\text{-}45\text{g Mg}^{-1}$ to the emission of particulate matter. The data given in Table 18 were quoted for emissions of undissolved solids (g Mg^{-1} based on 70% yield from coal):-

	Fresh Water	Process Water
Parallel-Sided		
Tower	205	410
Tapered Tower	880-946	1427-1816

Table 18

EMISSION RATES WITH CLEAN AND DIRTY MAKE-UP WATER

The increases when using process water make-up are much greater than would be expected merely from the suspended solids content of the process water. Clearly, some alternative mechanism is involved.

In a review of similar work (46) by the U.S. Environmental Protection Agency, comments were also made concerning anomalies in the ratio between the steady-state equilibrium concentration of dissolved solids in the recirculating water from the coke breeze settling ponds, and of the water used for make-up. In some cases, the dissolved solids concentrated two-fold and more in the settling ponds, whereas in other cases the ratio was 1:1 or even less. These anomalies were not resolved in the review.

The following explanation is proposed. The determining factor will be the composition of the dissolved solids, or the form of hardness of the water. On striking the incandescent coke, any temporary (bicarbonate) hardness would be converted into insoluble carbonate, and a portion of this could be emitted as fine particulate CaCO_3 . (This might appear in external deposit gauges as undissolved or dissolved solids, depending on the pH of the collected rainfall.) Permanent hardness, on the other hand, would be unchanged during the quenching operation. Evaporation of the steam would thus cause an increase in dissolved solids content due to permanent hardness, but this would be offset by the "softening" action of converting bicarbonate into carbonate.

The overall effect on the composition of the recirculating quench water would thus depend on the composition of the make-up water. Relatively hard, fresh make-up water would probably be softened overall, whereas boiler blow-down water would give rise to very high dissolved solids in the quench water. It is probable that the anomalies in the results by the U.S.E.P.A. can be explained in this way.

In the U.S.A., some counties have set conditions that require the make-up water to be of "Lake Quality" or better(47). No such legislation exists in the U.K. at present but the evidence in sections 3.4 and 3.5 indicates that controls along these lines may be required in future.

CHAPTER 4

CONTROL OF THE COAL CARBONISATION PROCESS

4.1 THE SITUATION AT THE START OF THIS WORK

It has been shown that the installation of equipment to improve grit arrestment in quench towers gave rise to deposition values for undissolved solids in the more distant gauges which were close to background levels, but left relatively high deposition values in the nearby gauges.

This indicated another source of contamination which was more local in its impact. The most visually intrusive emissions in that area arise during the discharge of under-carbonised coke. Hence, the experiments in Chapter 4 have been designed to minimise the emissions from such discharges, and to determine the influence of such emissions on deposition in the surrounding gauges.

4.2 GENERAL DESCRIPTION OF COKE OVENS

The coke oven plant at B.S.C. Llanwern, where the experiments on carbonisation control were carried out, contains up to 140 ovens of 4m height, and 53 ovens of 6m height.

The ovens are in the form of long slot-type chambers of tapered construction. They are narrower at the ram-side (pushing side) and wider at the coke-side (discharge side), with a mid-point width of 450mm. There is an overall taper of 75mm. The taper eases the discharge of the coke by means of the pushing beam.

The 4m ovens take a charge of circa 20Mg of finely-crushed coal feed, and produce circa 13-14Mg of coke per charge. The 6m ovens take circa 30Mg of coal feed, and produce circa 20-22Mg of coke per charge. A coke oven battery may contain 30 or more ovens, and production is batch-wise.

The ovens are constructed of refractory bricks with a high heat transfer coefficient.

4.3 THE CARBONISATION PROCESS

Finely-crushed coal, containing on average around 10% moisture, is fed by gravity into the ovens from a charge car. A sequential method of charging the various ports is used to minimise emissions.

The ovens are heated indirectly by means of flues sited between the ovens. Heat is recovered from the exit gases in regenerators, and the flows are reversed every 30 minutes. The fuel used is either coke oven gas or blast furnace gas. As the coal is heated, volatile matter is driven off and recovered in the by-products plant. The heating process lasts of the order of 18h for blast furnace coke, and longer for foundry coke. After 18h carbonisation, the coke temperature should be in excess of 1570K on the discharge side of the oven.

The relative rate of evolution of volatile matter towards the end of the carbonisation cycle is shown (37) in Fig.44. This indicates the importance of adequate carbonisation, and shows the large increase in smoke emission that arises if ovens are discharged early. It has been reported by British Carbonisation Research Association(37) that reducing the carbonisation period by say 5%, that is, a reduction of 45min., will increase the smoke emission to 400-500% of that with adequate carbonisation. The wisdom of designing coke oven pollution control equipment to cope with such excessive emission rates has been questioned(37).

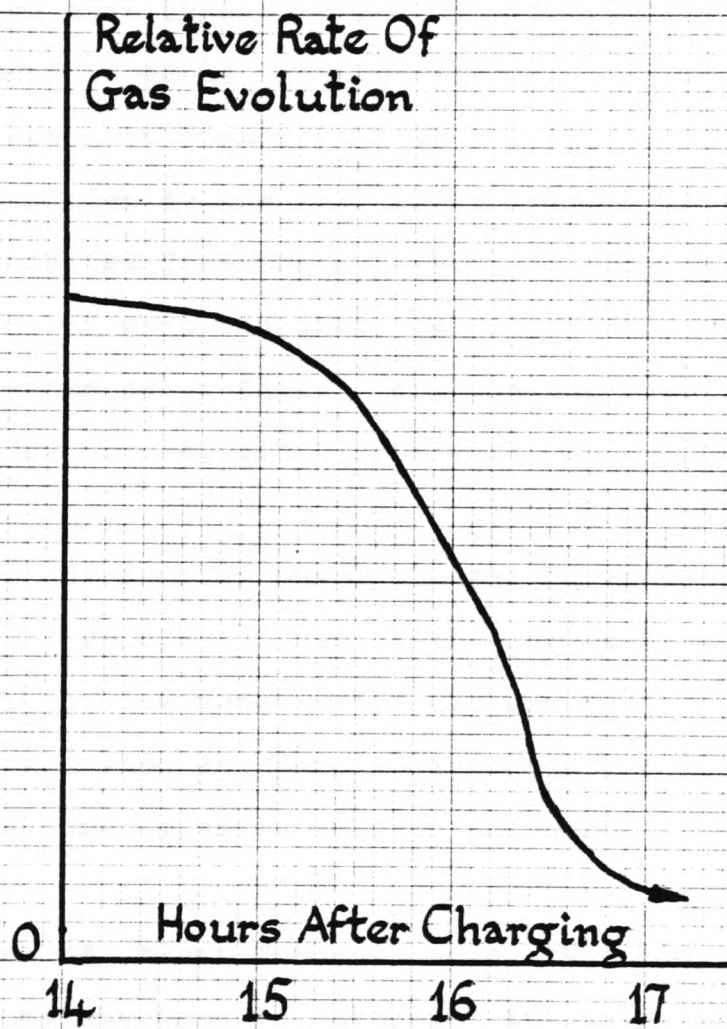


Fig. 44

Fall in Gas Evolution At End
Of Coking Period

On completion of carbonisation, the oven doors are removed, and the incandescent coke is discharged into a special type of rail-car, for transport to the quench tower, where it is rapidly cooled with water sprays.

The emissions which occur on oven discharge can be classified into two main types:-

- (a) Emissions of smoke due to incomplete carbonisation. These are most commonly from the ends of the ovens, and give rise to the term "black ends", although they can also arise from the main body of the coke.
- (b) Emissions of grit and dust, usually caused by fracture of the coke as it falls into the rail-car, particles then being carried aloft by thermal updraughting.

In production of foundry coke, longer carbonisation means that the coke generally has little remaining volatile matter, and is of low reactivity. In general, virtually no smoke is emitted when an oven is discharged, although there will still be some emission of grit and dust.

In production of blast furnace coke, the policy amongst western nations has been to attempt to make a reactive product. The shorter carbonisation period leads to greater emissions of grit and dust on discharge, and there can be much smoke in the emissions. Over the years, this has been the cause of justified complaint from householders in the vicinity of coke ovens, not merely from visual intrusion, but also from deposition of grit and dust.

Considerable effort has been put into attempts to control this problem, both by the companies concerned, and by the regulatory authorities. Most methods were unsuccessful because they lacked the ability to express the control system in numerical terms relating to the carbonisation process. Without such a link, and without the setting of consistent numerical standards, it was usually found that the initial resolve diminished with the passage of time.

The following sections describe the development of a numerical control system at one coke works, which has brought a significant improvement in control to the carbonisation process. The effect on the emissions of particulate matter has been evaluated in Chapter 2, and shown to be very beneficial.

4.4 A SYSTEM FOR CLASSIFYING DISCHARGE EMISSIONS

The first experiment involved the development of a system of classifying the "quality" of the emissions on discharging the ovens. This needed to be simple and straightforward, and to mirror the reactions of external householders.

The development of such a system had been shaped during observations made at a distance of circa 1500m from the coke ovens while carrying out time-lapse photography. These had shown that, in very general terms, the emissions could be classified into three grades, which became known as the Pushing Emission Grades (P.E.G.), when viewed from that distance. These grades could be defined as follows:-

GRADE 1 Difficult to distinguish from normal heat haze, consisting of grit and dust, with virtually no smoke. Little visual intrusion. Discharge only apparent due to steam plume from quenching.

GRADE 2 Grey cloud observed during the discharge, caused by the presence of smoke in the emission. Visible at a distance, but disperses fairly rapidly, and unlikely to cause serious external complaint.

GRADE 3 Dense black cloud, persisting for a long distance. Likely to cause serious public complaint.

No attempt was made to quantify the relative magnitude of the emissions from each of these grades, but based on reported work by B.C.R.A.(37), it is probable that there was a factor of circa 5x at least between Grades 1 and 3.

For control by plant personnel, it was then necessary to correlate the distant observations with those made within the local plant area, of coke discharges. It is standard practice on coke ovens to carry out surveys of smoke leakage from doors, charge lids etc., using the B.C.R.A. method (41). For these, there is a standard viewing distance of 20m, and it was decided that a standard set of photographs would be prepared for classifying oven discharges when viewed from that distance. To this end, a large number of colour photographs were taken, and agreement was reached between the author and B.S.C. staff on those which most closely corresponded to the various grades. These were then mounted in transparent plastic folders for reference.

The method of monitoring carbonisation is to check 3 temperatures along the length of the ovens - towards the ram-side, in the middle, and towards the cokeside. Each of the grades thus had 3 photographs corresponding to the above parts of the coke product on discharge from the oven. It proved a relatively easy matter to categorise discharges into one of the above grades, so that a satisfactory system of classification had been devised. Copies of the photographs are shown in Figs.45-47.



Cokeside - Grade 1



Centre - Grade 1



Ramside - Grade 1

Fig. 45



Cokeside - Grade 2



Centre - Grade 2



Ramside - Grade 2

Fig. 46



Cokeside - Grade 3



Centre - Grade 3



Ramside - Grade 3

Fig. 47

4.5 INTERIM TARGETS FOR DISCHARGE EMISSION QUALITY

It was agreed with the company that experiments would be conducted to establish the conditions which gave rise to Grade 3 emissions. On an interim basis, it was also agreed that an acceptable standard had been achieved if Grade 3 emissions were eliminated.

To achieve this improvement, knowledge on the time/temperature relationship in coke production was needed.

4.6 RELATIONSHIP BETWEEN OPERATING TEMPERATURES AND PUSHING EMISSION GRADES

Having established a satisfactory method for classifying pushing emissions, agreement was reached with the company on an experiment to determine the relationship between the known operating parameters and the resultant P.E.G.

It was decided that no additional operational data would be collected, other than that normally recorded on the shift log sheets. For this experiment, the following data were recorded for each discharge:-

Relevant Flue Temperature

Scheduled Carbonisation Period

Fuel Gas In Use

With regard to the fuel gas, published data normally refer to firing with coke oven gas, whereas at this works there is also the option of firing with blast furnace gas, which has a lower calorific value. Practical experience has shown that to achieve an equivalent thermal input, the temperature measured at the burner block needs to be circa 30°C higher for coke oven gas firing than for blast furnace gas firing. Therefore, when blast furnace gas was in use, recorded temperatures have been increased by 30°C.

A total of 118 oven discharges were monitored in this way, 60% of which were on the 4m ovens, and 40% on the 6m ovens. At the time of the observations, 193 ovens were in service

and observations were on a random basis, so clearly not all ovens were monitored in this experiment. Observations were made by company technical staff well trained in performing smoke leakage surveys; and can be considered reliable.

NOTE

Observations came to a halt at this point due to a company reorganisation, involving some staff reductions, and observers were deployed on other duties.

Of the discharges noted on the 4m ovens, many were classified as Grade 1, some of which resulted from extended carbonisation periods due to delays in the production schedule caused by breakdowns. Thus there was only a limited number of Grade 3 discharges, and there was much doubt as to whether there were enough for a valid analysis. However, for a preliminary evaluation, it proved possible to sub-divide the results according to carbonisation period, that is, either above or below 20h, and one important conclusion could be derived, as shown in section 4.7.

It should be noted that, to inexperienced observers, it may appear that even Grade 1 emissions give rise to considerable emissions of particulate matter when viewed from near the ovens. Such emissions consist principally of small coke particles which have not agglomerated into the main body of coke, or which are released when the massive coke falls into the rail-car, but do not result from under-carbonisation.

To overcome this observational problem, the following alternative system of classification can be used, based on the appearance of the coke in the rail-car on its way to the quench tower. This system was developed after the original experiment had been completed. It would be suitable for reports by the rail-car drivers on pushing emission grades:-

GRADE 1 No visible smoke; only heat haze.

GRADE 2 No visible smoke; some fume apparent.

GRADE 3 Product still burning with luminous,
smoky flame in parts of rail-car.

4.7 PROBABILITY ANALYSIS ON 4m OVEN DISCHARGES

To simplify the analysis, the recorded flue temperatures were grouped into 50°C ranges, and the percentages of Grade 1 and Grade 3 discharges in each range were calculated, based on the total number in each range for carbonisation periods of 20h or less. This was done for the ram-side and the coke-side only, as the oven middle section discharges were of acceptable quality in general. The results of this analysis are shown in Tables 19 and 20, and in Figs. 48 and 49. Where only one discharge was seen in any temperature range, the "distribution" has to be treated with caution, and such results have been omitted from the graphs.

It can be seen from Fig.48 that at the highest recorded temperatures on the ram-side, Grade 3 emissions could be prevented, whereas on the coke-side there remained an unacceptable level of Grade 3 emissions at those temperatures. The conclusion is that it would only be practicable to achieve acceptable discharges from the coke-side of the ovens by extending the carbonisation period beyond 20h, taking into account the condition of the ovens at that time. Such a method of operation would also produce acceptable carbonisation on the ram-side of the ovens.

These conclusions were confirmed by a more detailed analysis of all discharge emissions, based on their relationship with the operating curves for coal carbonisation, as described in the next section.

Temp. Range (K)	G1	G2	G3	Total	%G1	%G2
1323 - 1372	0	0	3	3	0	100
1373 - 1422	3	1	5	9	33	56
1423 - 1472	2	1	6	9	22	67
1473 - 1522	3	0	4	7	42	57
1523 - 1572	4	3	3	10	40	30
1573 - 1622	3	2	0	5	60	0
1623 - 1672	1	0	0	1	100	0

Table 19

RAM-SIDE PROBABILITY DISTRIBUTIONS

Temp. Range (K)	G1	G2	G3	Total	%G1	%G2
1323 - 1372	0	0	1	1	0	100
1373 - 1422	0	0	0	0	-	-
1423 - 1472	0	0	0	0	-	-
1473 - 1522	0	1	2	3	0	67
1523 - 1572	2	5	1	8	25	12
1573 - 1622	2	2	9	13	15	69
1623 - 1672	2	3	6	11	18	55
1673 - 1722	3	4	3	10	30	30

Table 20

COKE-SIDE PROBABILITY DISTRIBUTIONS

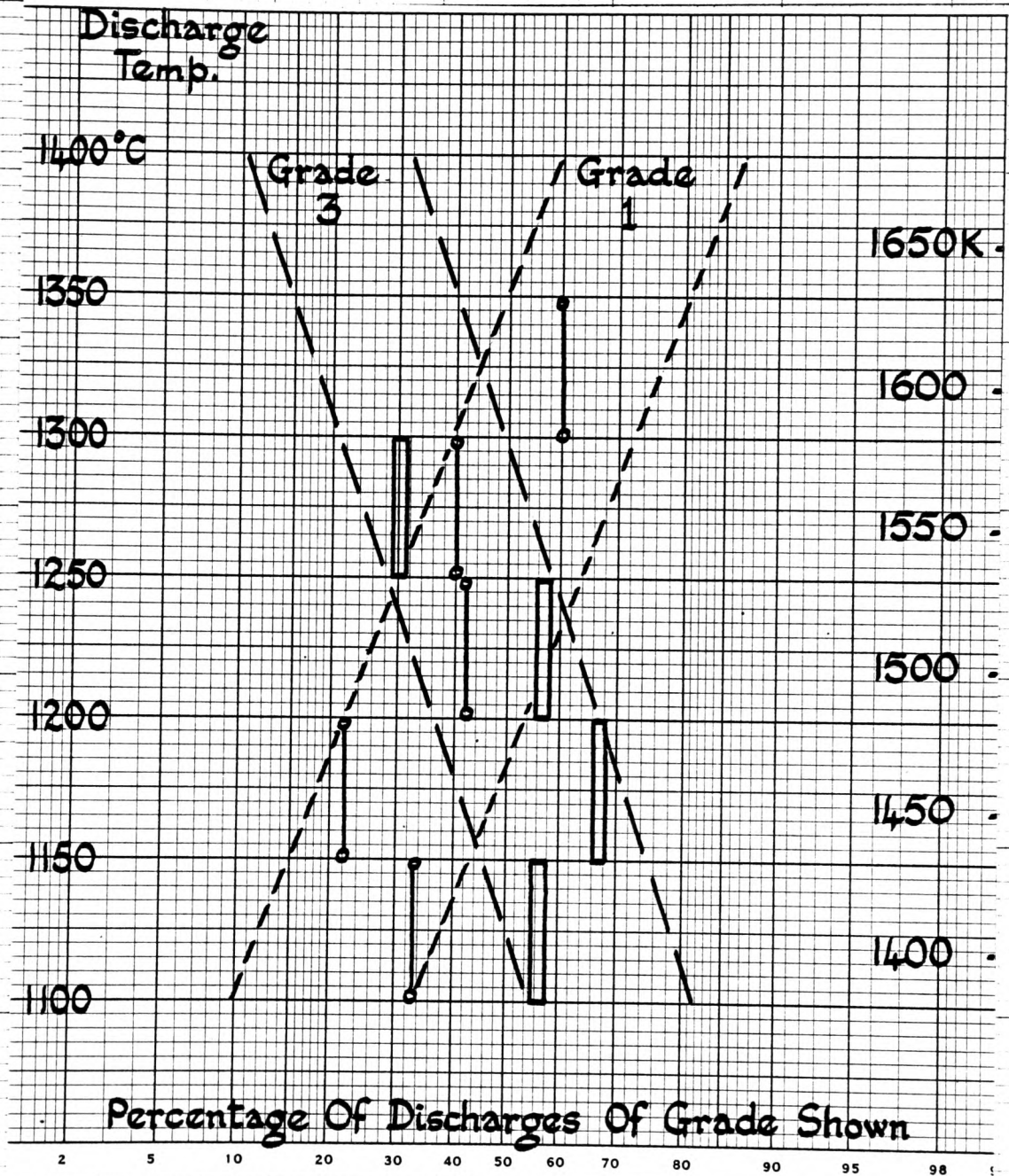


Fig. 48
 Ramside Probability Curves
 For G1 And G3 Discharges

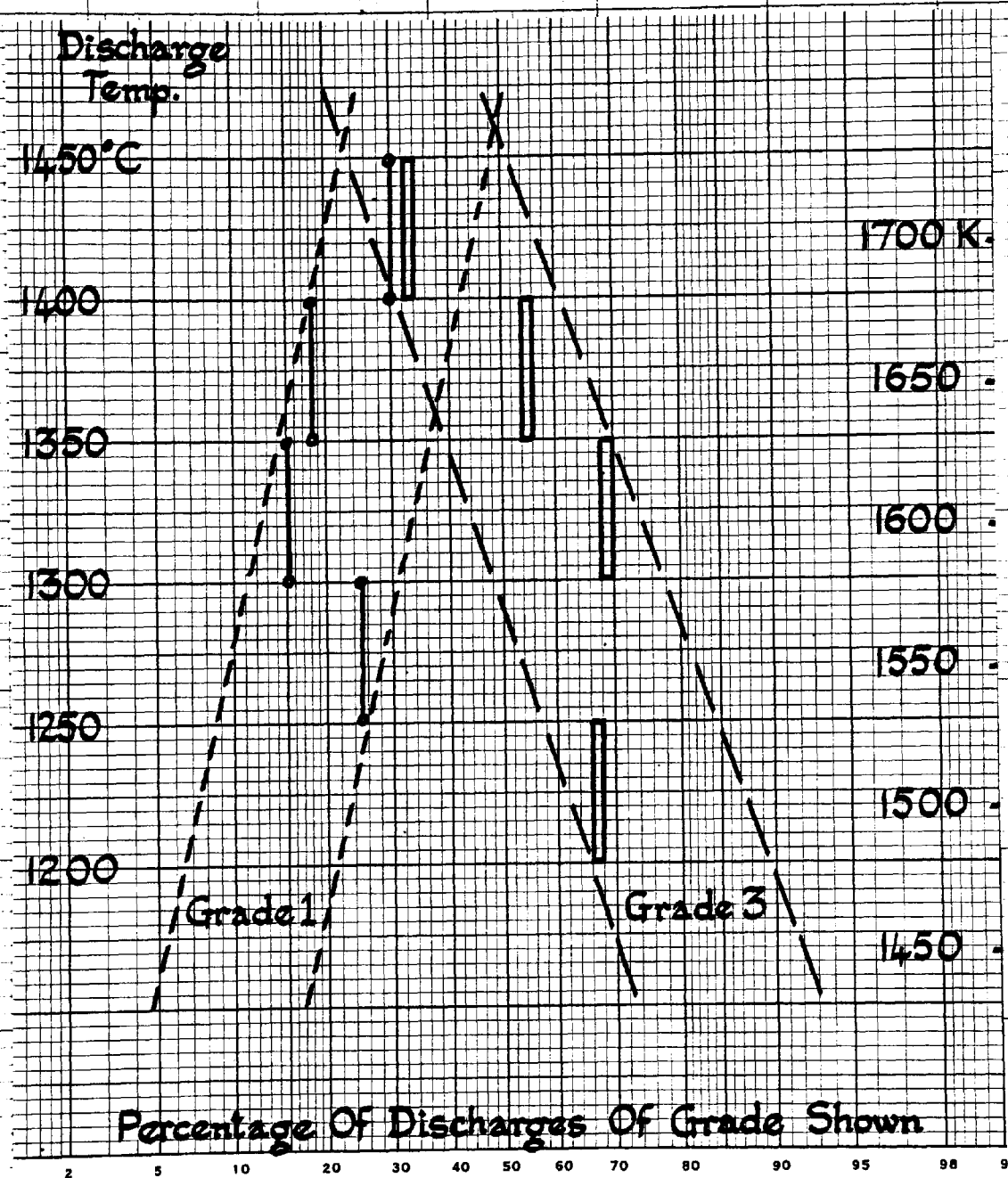


Fig. 49
Cokeside Probability Curves
For G1 And G3 Discharges

4.8 THE OPERATING CURVES FOR COAL CARBONISATION

The relationship between the temperature in the heating flues and the time required for satisfactory carbonisation follows the general shape shown in Fig.50 for the middle of the oven (39). The required flue temperature will vary across the length of the oven, being lower at the ram-side and higher at the coke-side. The operating curve supplied by the manufacturer, Otto-Simon Carves Ltd., relates to a mean chamber width of 450mm. This had been derived from work done at the Bergbau Forschung in Germany(2) on the basis of a Ruhr coal of bulk density 820kg m^{-3} , a heat of carbonisation of 2093 kJ/kg and 10% moisture content.

In order to estimate the operating curves which would correspond to the flues where the routine monitoring temperatures were taken, further operating curves were obtained (2) relating to oven chamber widths of 400mm and 500mm. These were then interpolated to give operating curves for oven widths of 430mm and 480mm, corresponding to the monitoring points shown in Fig.51. These derived curves are given in Fig.52. It can be seen that the derived flue temperatures needed when firing with coke oven gas for a carbonisation period of 18h are:-

Ramside	1525K
Middle	1545K
Cokeside	1570K

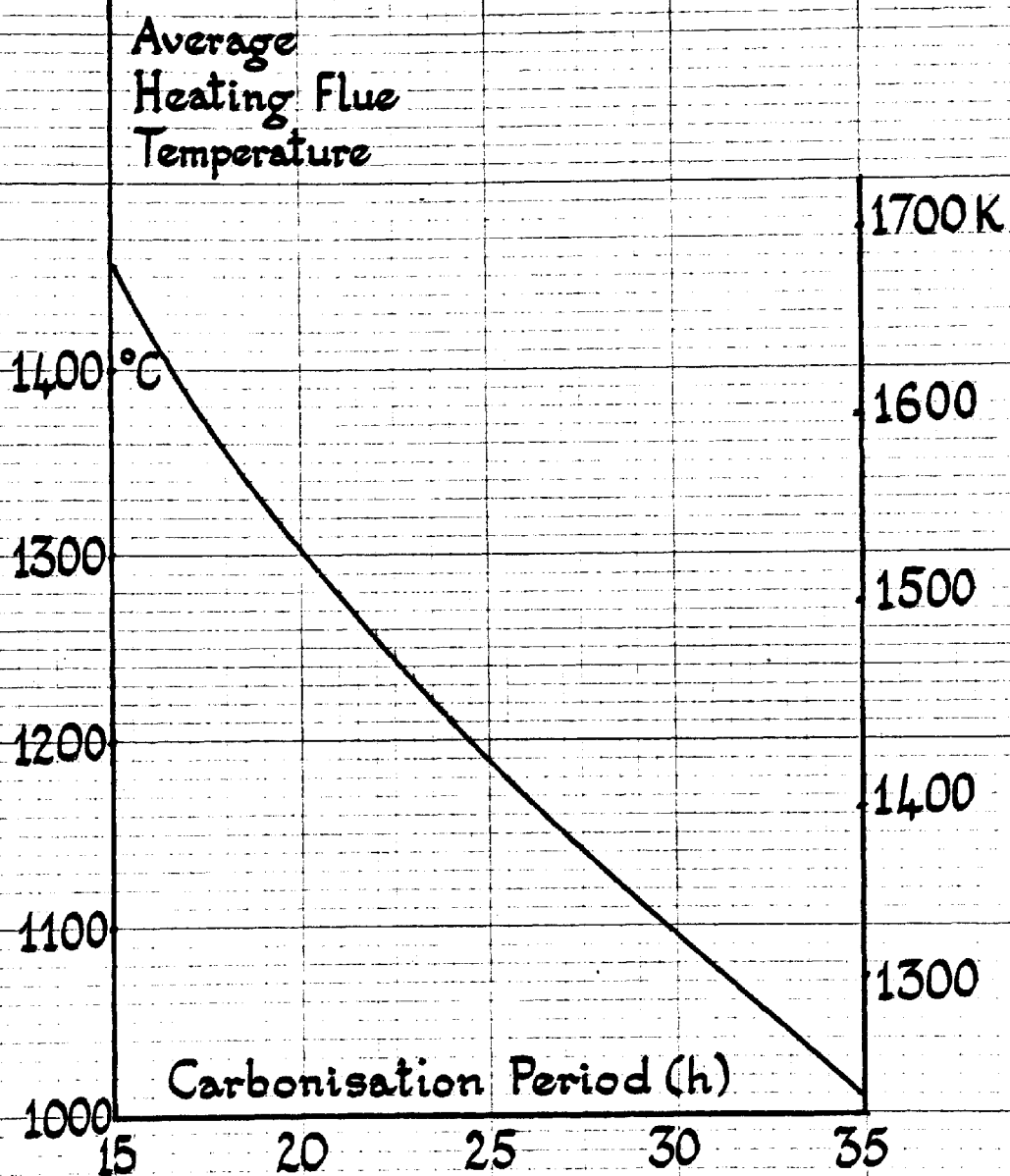


Fig. 50
General Operating Curve
For Coal Carbonisation.

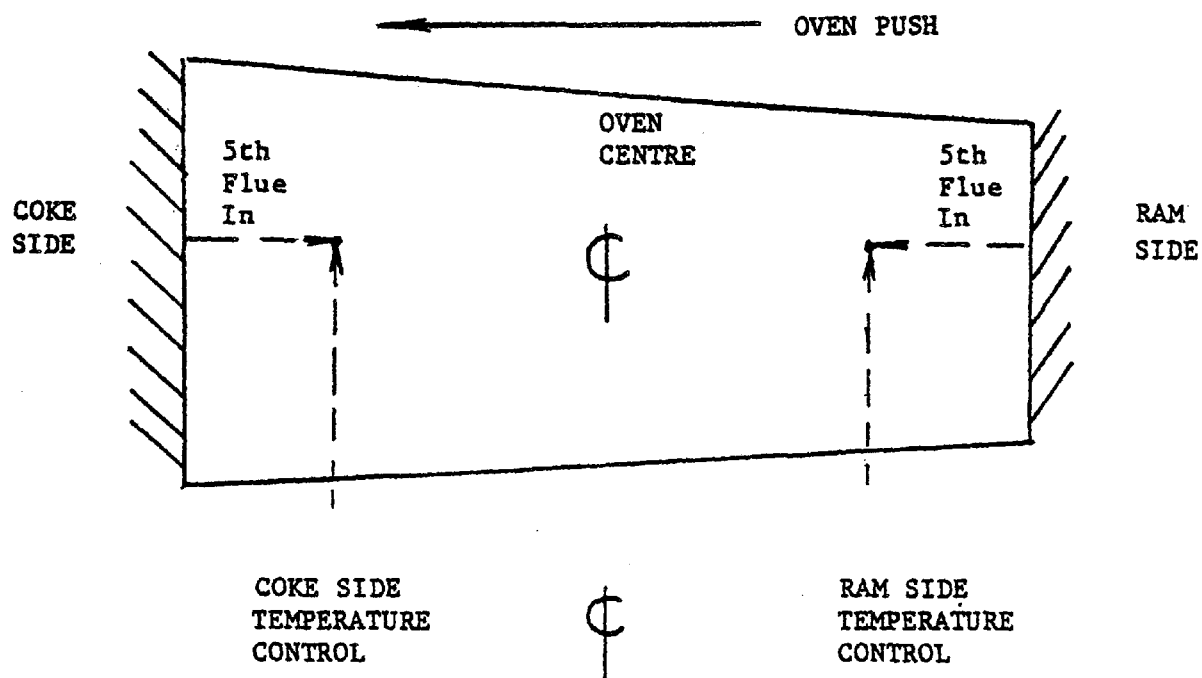


Fig.51

Schematic View Of Coke Ovens
Showing Temperature
Measurement Points

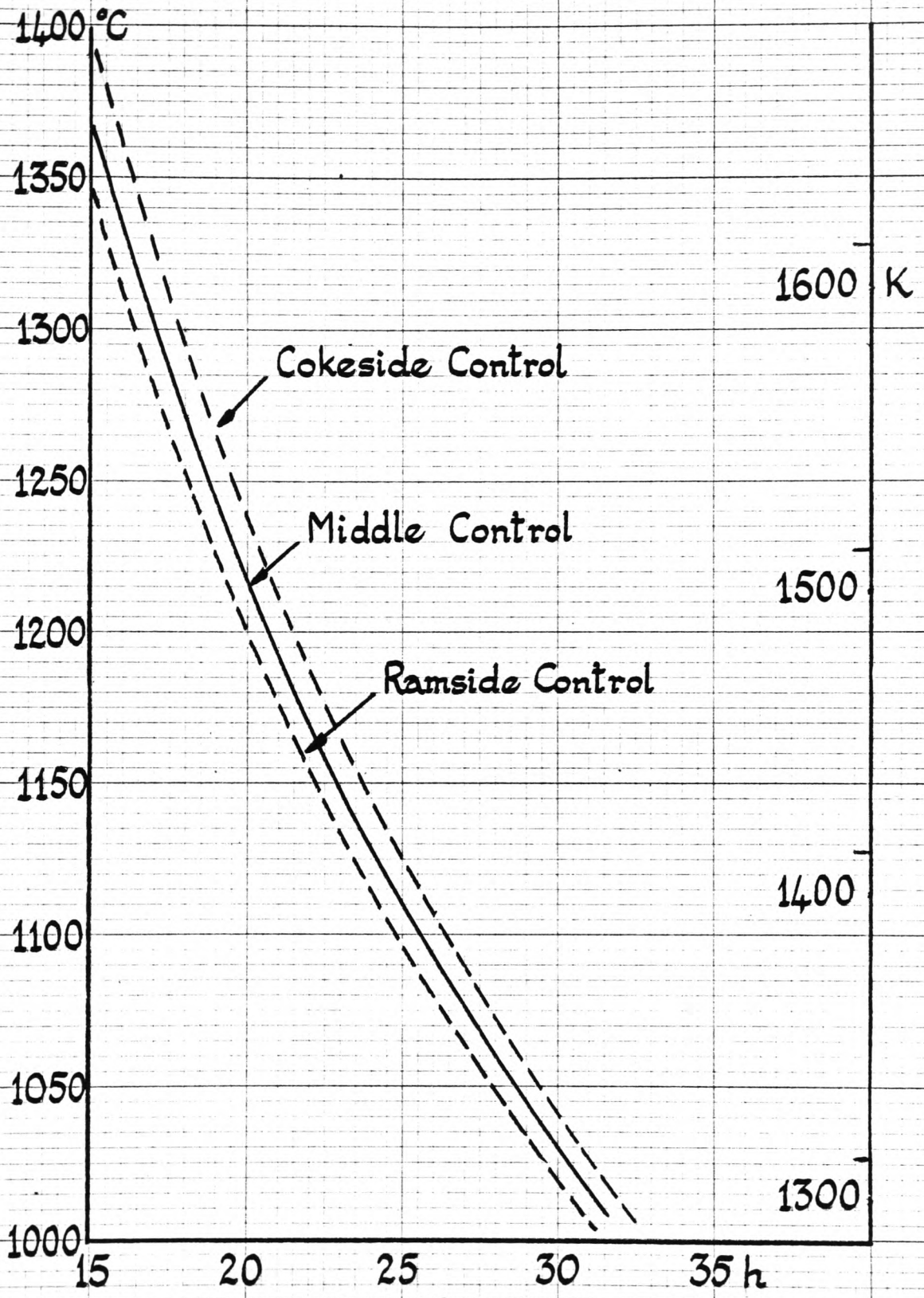


Fig. 52
Carbonisation Curves In Use
At B.S.C. Llanwern

4.9 THE CARBONISATION OPERATING CURVES AND PUSHING EMISSION GRADES

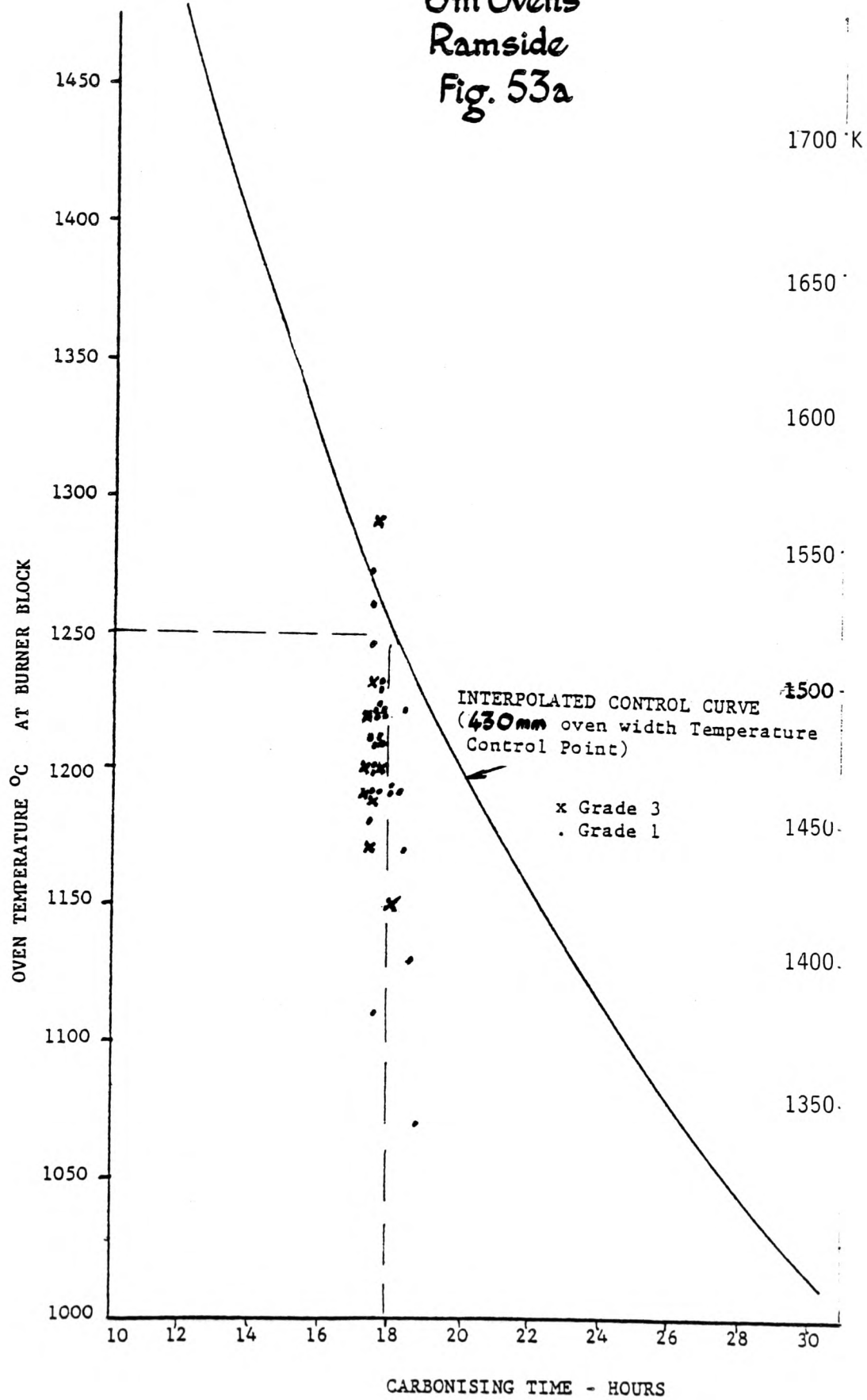
The conclusions from section 4.7 were confirmed by examining the relationship between the operating curves and the pushing emission grades. This was done by considering only the operating curves for the outer temperature monitoring points (since the oven middle was in general acceptably carbonised), and marking on the curves the operating points relating to Grade 1 and Grade 3 discharges only.

For the 6m ovens, this showed that the operating curves were in general acceptable indicators towards satisfactory emissions on oven discharge, and that operating conditions could often be well below those required by operation of these curves, without Grade 3 emissions being recorded, as shown on Figs.53(a) and 53(b).

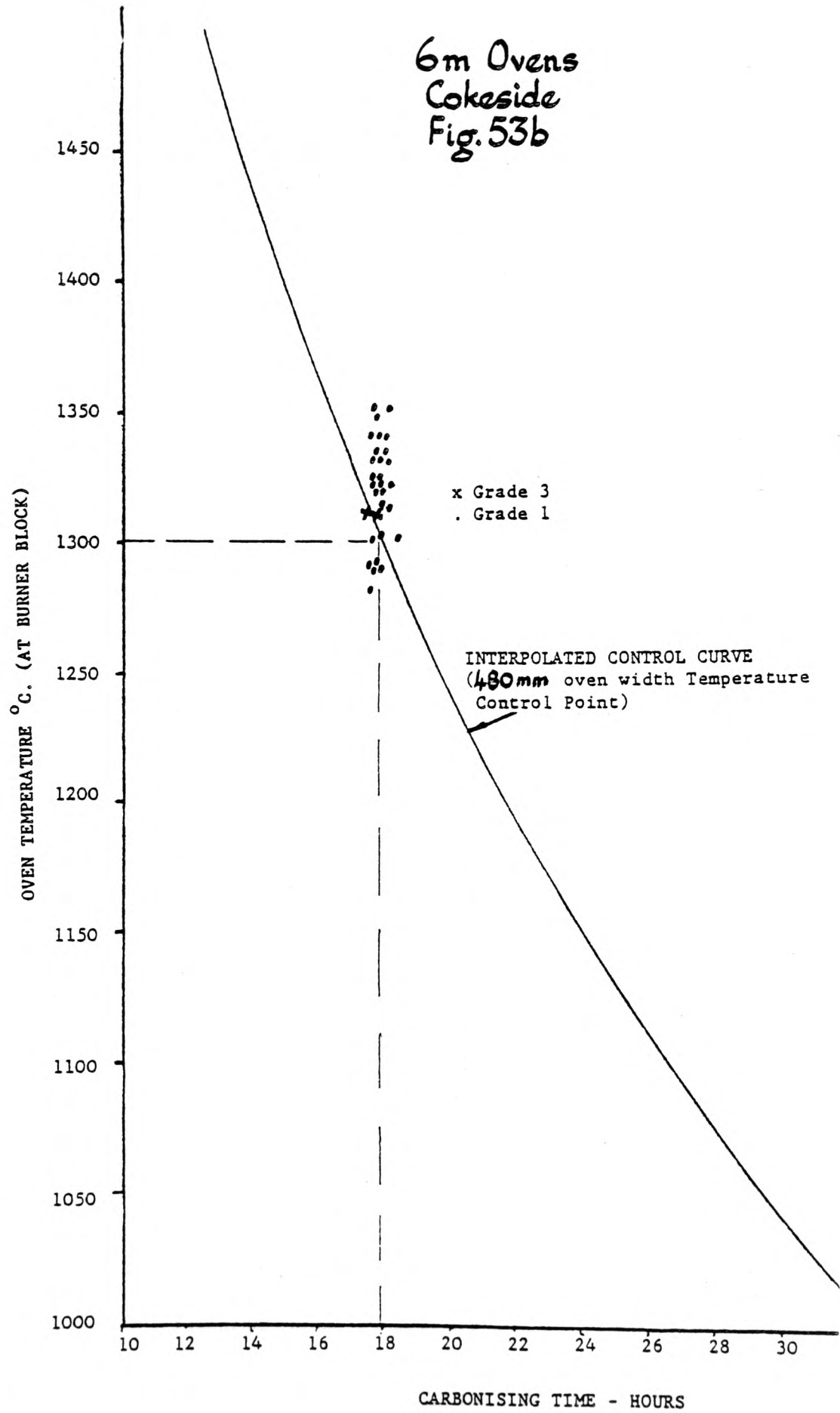
For the 4m ovens however, the situation was quite different. In this case, if the operating conditions were below the curve, there was a very high probability of a Grade 3 emission, while Grade 3 emissions were also being recorded when flue gas temperatures were up to 80°C above the operating curves, as shown in Figs.53(c) and 53(d).

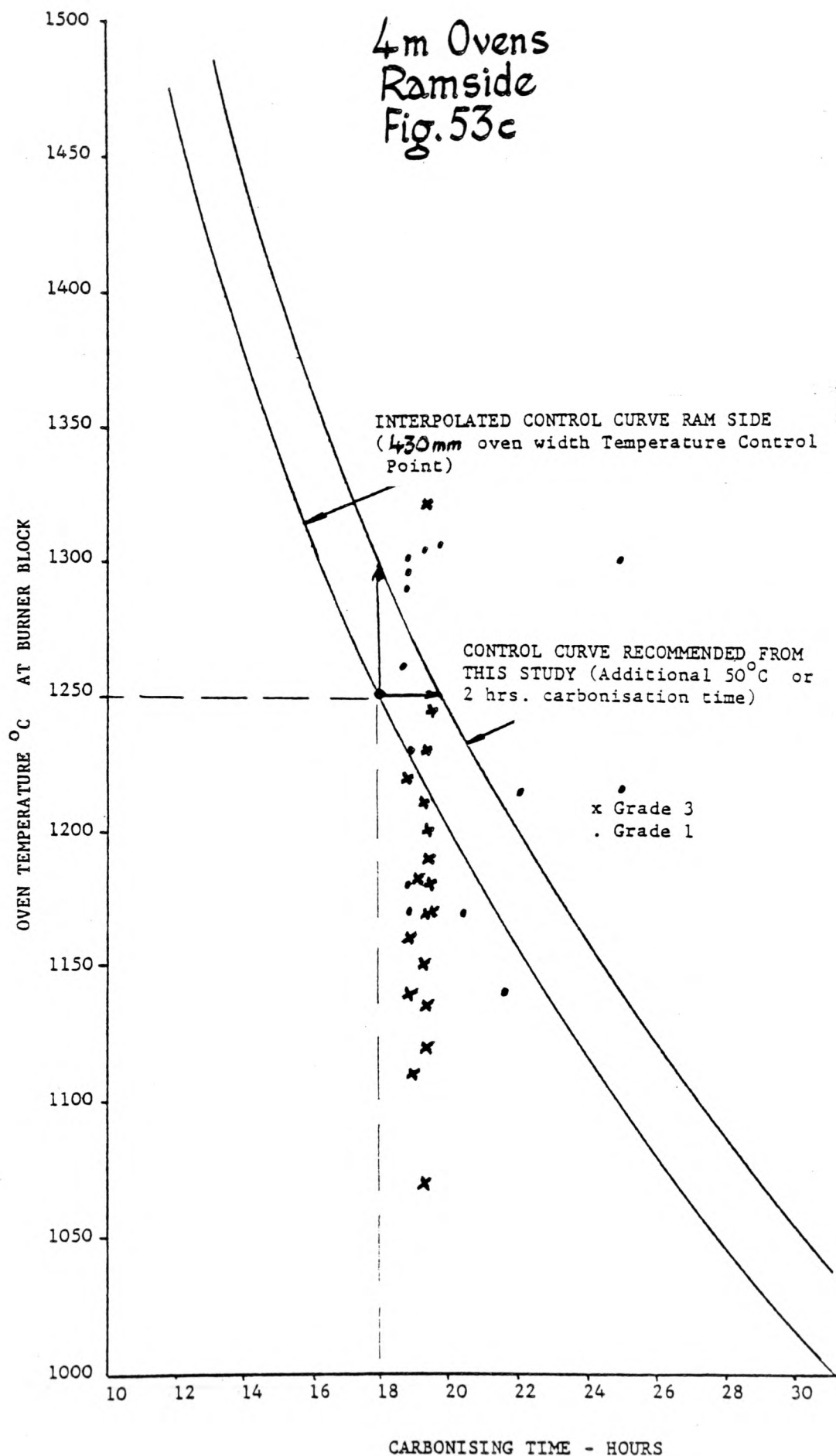
This part of the study was published as an internal report by B.S.C. Llanwern (45). As a result of the above examination, it was possible to establish the basis for an Interim Best Practicable Means for the works as follows:-

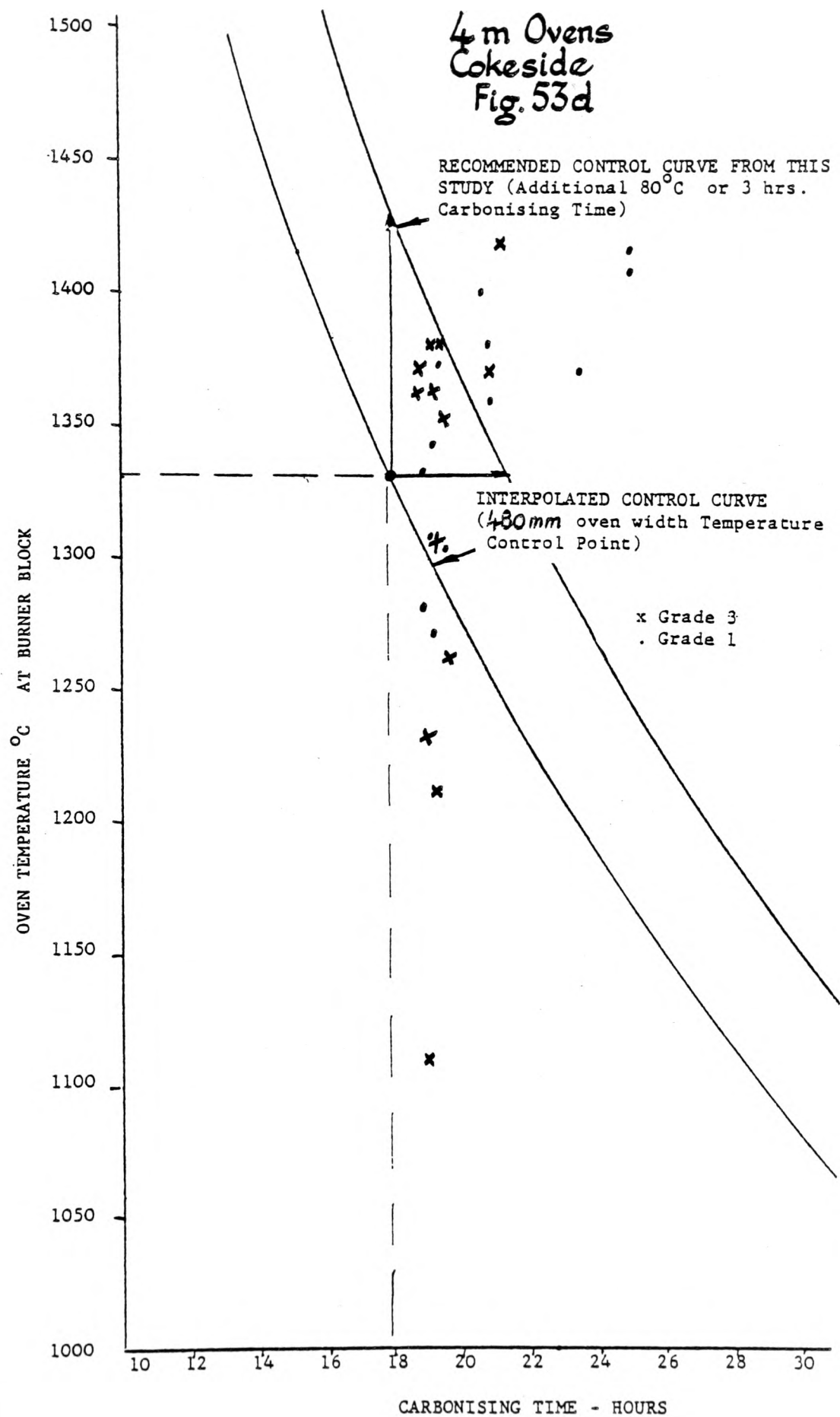
6m Ovens
Ramside
Fig. 53a



6m Ovens
Cokeside
Fig. 53b







- (a) For the 6m ovens, the working conditions should be maintained on or above the derived operating curves, as in Figs. 53(a) and 53(b).
- (b) For the 4m ovens, the working conditions should follow alternative operating curves, as in Figs. 53(c) and 53(d).

This experiment led to the company setting higher targets for the shift average temperature, as the first strategy.

NOTE

The strike during the first quarter of 1980, while interrupting the observations for the above experiment, also provided the opportunity for observations of the discharge emissions on the 4m ovens at very extended carbonisation periods. As expected, there were no "black ends", and it became clear that an intermediate position could be found following the strike, where production could be increased, but not to the point where undercarbonised ovens were discharged, by following alternative operating curves.

4.10 MANAGEMENT INFORMATION - SHIFT AVERAGE TEMPERATURE

If the batteries are heated correctly, such that there is a graduated increase in temperature from the narrow ram-side to the wider coke-side, the average temperature over the whole battery will correspond to that given by the 450mm operating curve. On the assumption therefore, that the monitored temperatures are not far removed from the operating curves, the Shift Average Temperature is then an important control parameter as far as management information is concerned. Senior coke oven management staff will be aware of the pushing schedule, and will know the temperature required for adequate carbonisation, for comparison with the actual Shift Average Temperature.

However, if the variance in the flue temperature measurements is high, that is, if the temperatures vary greatly above and below the operating curve, it can be seen that the Shift Average Temperature is not an adequate control parameter in that it will not indicate whether undercarbonised material is being produced. Also, in an effort to maintain the Shift Average Temperature at the level called for by the operating curve, there will be a tendency to overheat certain ovens in order to compensate for those with lower temperatures. Operation at higher temperatures than necessary will only accelerate maintenance problems, and should be avoided whenever possible.

The proposed alternative operating curves derived in section 4.9 show that to improve the degree of carbonisation, several options were available:-

- (a) an increase in flue temperatures, obtained by increasing the heat input, or
- (b) an increase in period of carbonisation, obtained by reducing the number of ovens discharged per shift, or
- (c) a combination of the above two.

4.10.1 STRATEGY 1

To follow the revised operating curves by increasing the Shift Average Temperature target, i.e. by increasing the total heat input.

This was designed to achieve the objective at a higher energy cost, but without loss of production. It only had a marginal effect on the "cooler" ovens, but caused marked overheating on the good ovens. On occasions, there was incipient fusion, causing the coke to "stick" in the oven, and giving great difficulty in discharging. This presents quite a hazard, and is unacceptable as a regular method of operation.

4.10.2 STRATEGY 2

Adopted after a relatively short period, was to increase the period of carbonisation and to operate with less-elevated temperatures.

This led to some improvement on the "cooler" ovens, and the company then entered into a long-term commitment with contractors to clean out the blocked flues which were causing the poor heat transfer. In view of the restriction in production caused by this strategy, it was possible to quantify the benefit from the recovery of the blocked flues and this justified the cleaning operation.

In the meantime, production continued on a compromise basis which attempted to minimise under-carbonisation on the "cooler" ovens, while preventing over-carbonisation on the good ovens. However, it only required a slight plant upset or an increase in the moisture content of the coal, for under-carbonisation once more to become a problem.

At that time, moisture content of the coal feed was not a specific process control variable. It was used for calculation of the daily dry weight of coal charged, for coal purchase requirements, and for calculation of plant efficiencies. Methods of calculating the effect of changes in moisture content on heat input requirements have been published as a British Standard(20), and show that each 1% additional moisture content requires an additional heat input between 1-2%. Compared with the average 9%, the moisture content can exceed 12% on occasions, equivalent to the need for a reduction of 4-5 ovens per day on the 4m ovens to avoid under-carbonisation

Similarly, if there were malfunctions in the coal crushing plant, the bulk density of the charge would increase. As the ovens are charged by volume, the weight of coal charged would increase, and unless there was a change in heat input this would again give rise to under-carbonisation.

The control information in use at the time was not able to respond rapidly enough to changes such as this, in order to prevent under-carbonisation, and an alternative method for controlling the process had to be devised. The breakthrough on this came in September 1981, and led to the Carbonisation CuSum system of process control.

4.11 THE CONCEPT OF THE CARBONISATION CUSUM

There were two periods in September 1981 when complaints of under-carbonisation were received from nearby residents, and further complaints, referring to one shift in particular, were received in the final week of the month. A detailed evaluation was therefore carried out of the log sheet for that shift, which carried the relevant temperature data for the 4m ovens:-

	No. of Discharges	Average Deviation	Standard Deviation
Above Curve	51	+79 °C	42 °C
Below Curve	20	-97 °C	65 °C
On Curve	4	0	0
Overall	75	+28 °C	92 °C

Table 21

EVALUATION OF CARBONISATION TEMPERATURES - SEPTEMBER 1981

It can be seen that the Shift Average Temperature was 28°C above the requirement of the design operating curve for the scheduled production rate. Although there were 20 temperatures below the curve, these were more than offset by the 51 above the curve. This was a clear demonstration of the inadequacy of the Shift Average Temperature for the control of under-carbonisation. The following logic was therefore applied in order to obtain a numerical factor to characterise the amount by which the coke produced for that shift was under-carbonised.

It was shown in section 4.9 that for the 4m ovens there was a very high probability that a Grade 3 emission would be produced if temperatures were below the relevant operating curves. Attention was therefore concentrated on temperatures below the operating curves, and temperature above the curves were ignored.

A CuSum was then prepared over the whole shift, taking into account all recorded temperatures which were below the curves, whether on the ram-side, the middle, or the coke-side. The reference values were the temperatures indicated on the relevant operating curves, and to avoid handling negative numbers, the actual temperatures were subtracted from the reference values. The number obtained was termed the Carbonisation CuSum, and for the shift in question, it was 1940°C.

To put this one value into perspective, similar calculations were performed for the previous 30 shifts - a total of 90 CuSums, involving on average about 70 temperatures per shift, or a total of over 6000 calculations. This was the most fundamental part of the investigation. It was found that there were three peaks in the values of the Carbonisation CuSum over this period, with a maximum value of over 9000°C. For ease of presentation, the results are shown in Fig. 54 in the form of daily averages, and in Fig. 55 in the form of a frequency distribution.

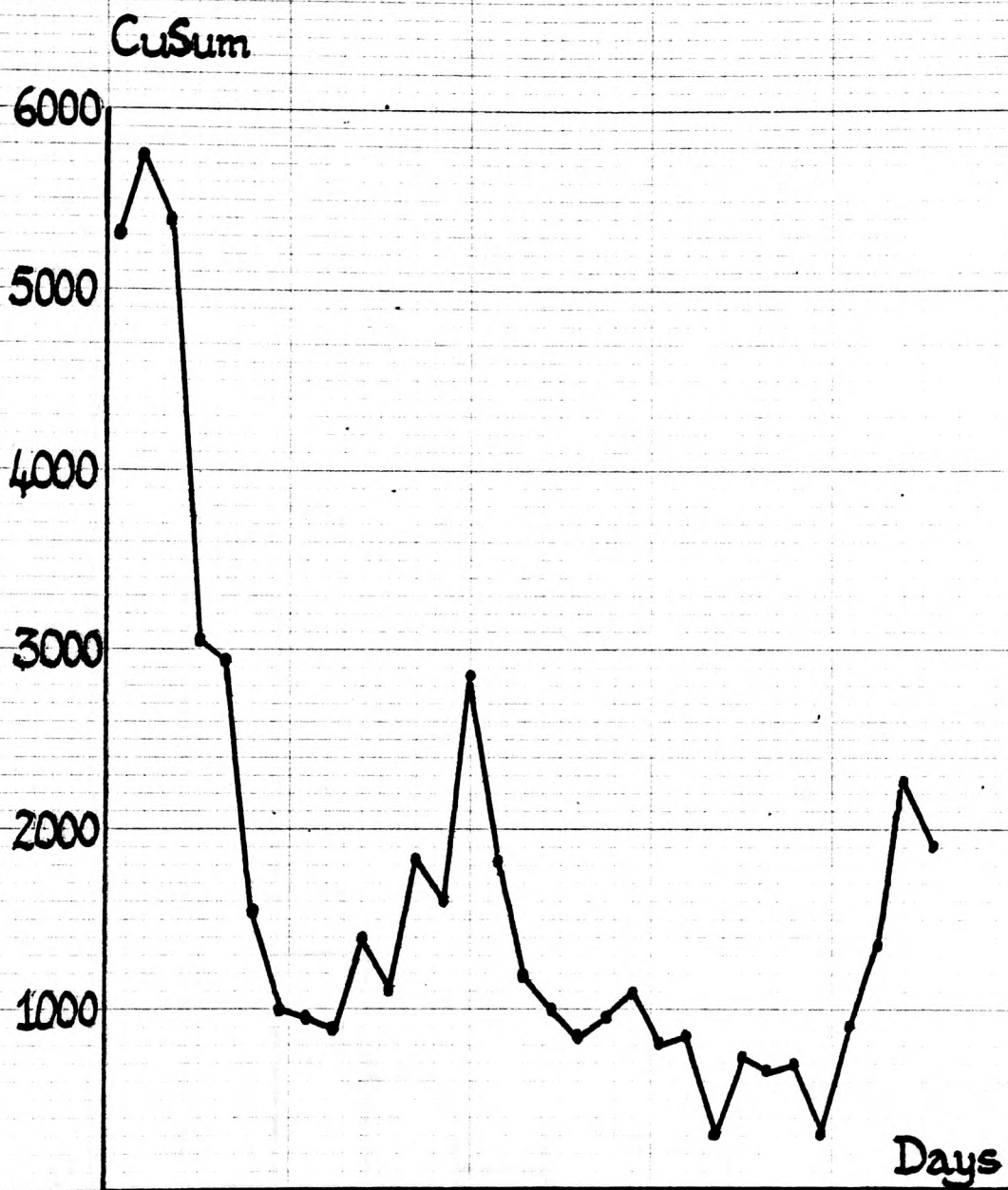


Fig. 54
Daily Averages of CuSums Aug./Sept 81
Before Introducing Control System

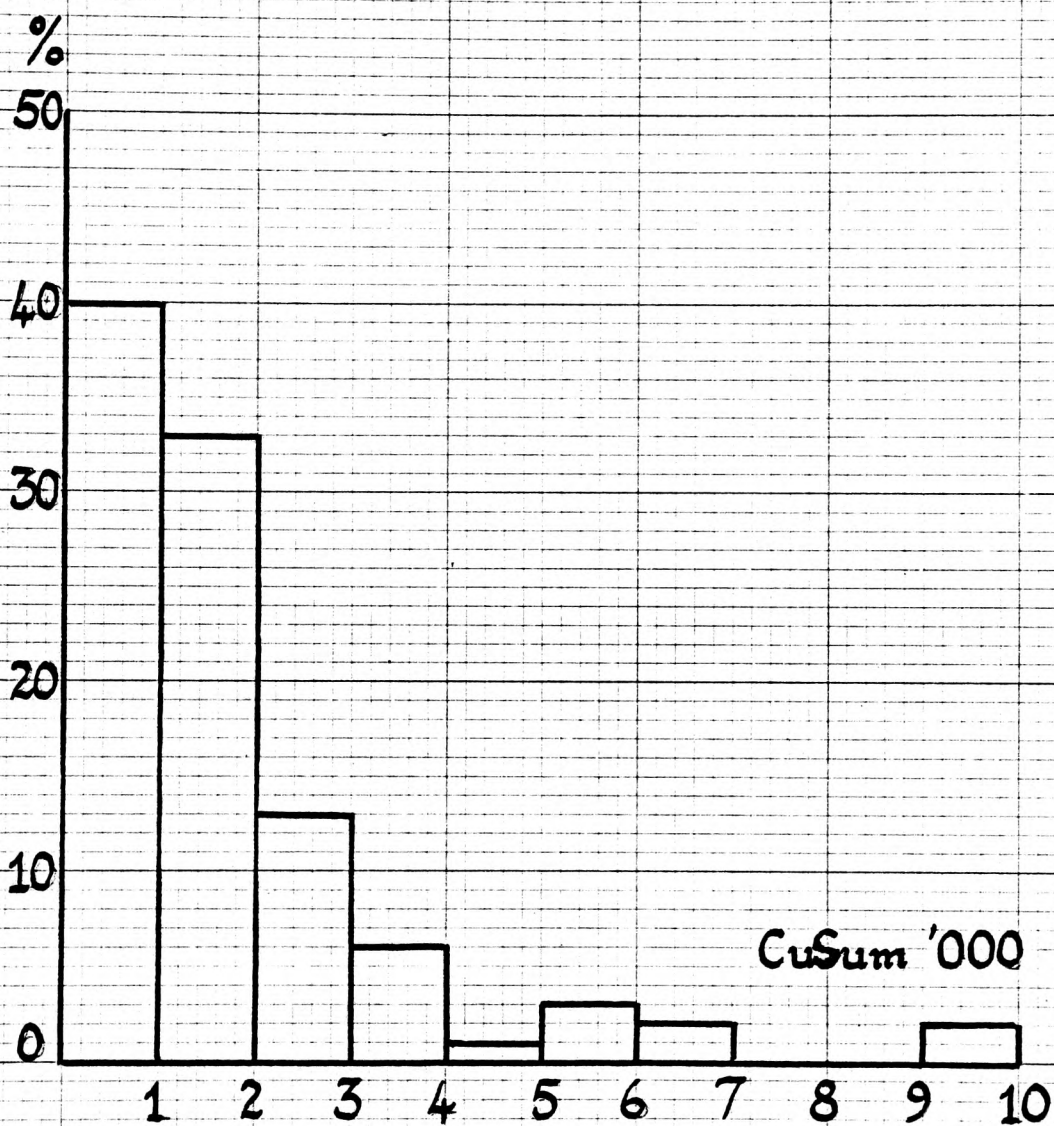


Fig 55
Percentage Distribution Of CuSums
Aug./Sept. 1981

The most significant discovery was that the peaks in the Carbonisation CuSums corresponded with the periods of complaint by nearby residents on account of undercarbonisation. This was most important since for the first time ever, the operating parameters over a full shift could be transformed into a number which had direct relevance as to whether unacceptable amounts of under-carbonised material were being produced. The other discovery was that, although at no time had the Carbonisation CuSum fallen to zero, there had been extended periods when there had been no external complaints. This implied that, under certain conditions, one could operate with some temperatures below the curves without giving rise to complaint.

The coke ovens manager accepted that the CuSum concept was valid, and negotiations were held to agree a value to be used for control purposes. Agreement was reached that operation of the 4m oven batteries would be permitted for a trial period at full-scale, using a CuSum limit of 1000°C per shift. The company agreed to take whatever action was necessary to hold the Carbonisation CuSum below 1000°C per shift. After preparation of the reference charts showing the temperatures called for by the derived operating curves for various pushing schedules, and for the two types of fuel gas, the system of control by Carbonisation CuSum began in November 1981. It was also agreed that the CuSum values would be calculated retrospectively on the following day shift, and that one man would be responsible for making any necessary changes in operating parameters.

4.12 CARBONISATION CUSUM CONTROL IN PRACTICE

4.12.1 STRATEGY 3

To maintain the Carbonisation CuSum below 1000°C per shift by increasing the total heat input, based on retrospective assessment of need.

Investigations were made to see if changes in the rate of underfiring would give the necessary changes in the Carbonisation CuSum, but it soon became apparent that the response time was too slow due to the inertia of the mass of firebrick in the system. In addition, "cooler" ovens were affected hardly at all because of their poor heat transfer, and although good ovens recorded temperature increases, these played no part in calculating the CuSum. This confirmed the findings from Strategy 1, but the demonstration via the Carbonisation CuSum was much clearer.

4.12.2 STRATEGY 4

To maintain the Carbonisation CuSum below 1000°C per shift by reducing the production schedule by one oven per day if the CuSum rose above 1000°C during any of the shifts on the previous day.

Agreement was reached that the changes in the CuSum would be achieved by reducing the number of ovens discharged in each day. The maximum rate of change recommended by the oven manufacturers was one per day. The converse would also apply, with regard to increases in production schedules.

This was a method of quantifying the changes made under Strategy 2, and the effect needs to be considered in conjunction with Strategy 5.

4.12.3 STRATEGY 5

To prevent any increase in production schedule which would cause the Carbonisation CuSum to rise above 1000°C in subsequent shifts.

Experience in the operation of Strategy 4 soon showed that the CuSum would have to be no higher than 600°C per shift to prevent this constraint coming into force. The application of Strategies 4 and 5 brought reasonable control on the 4m oven batteries within a matter of days, and control by Carbonisation CuSum soon became an established feature on the 4m ovens.

The degree of control during the next six months can be seen in Fig. 56, which indicates the maximum value recorded for the CuSum on any shift for the days during that time when the calculations were performed. All calculations were done manually at this stage, using a proforma of the type shown in Fig. 57.

As noted in Chapter 2, the improvement in the visual appearance of the discharges was most marked, and so was the reduction in the level of complaints. However, there were no apparent beneficial step changes in the Deposition CuSum for the two gauges sited in Llanwern village. In fact,

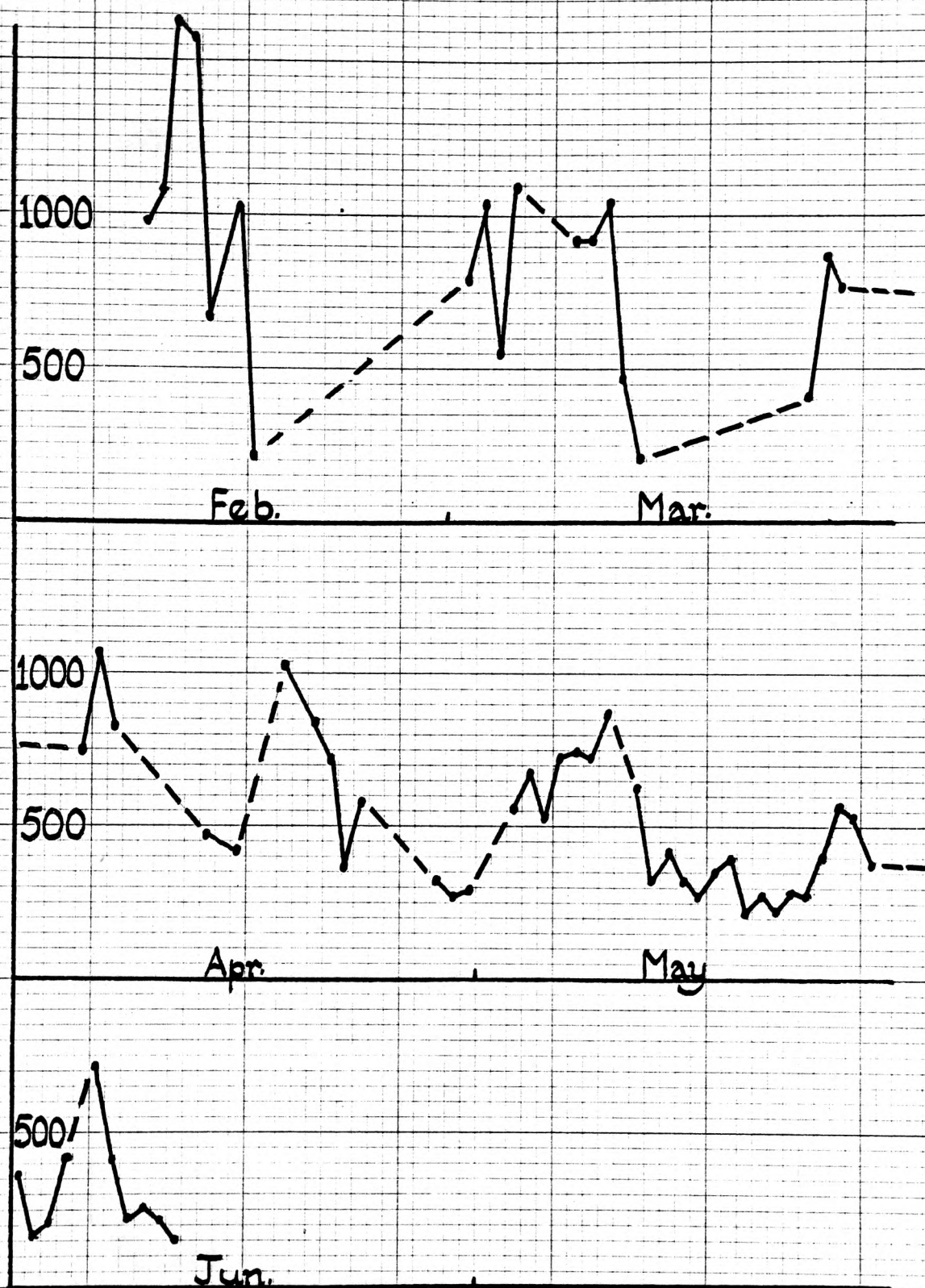


Fig. 56

Variation Of Carbonisation CuSum After
Introducing Control System

Date Shift

Targets	°C	°C	°C
---------	----	----	----

Negative Deviations

[illegible]

Carbonisation CuSum

Fig 5.7
A Proforma For Calculation

there were adverse step changes. As already noted, this could not have been caused by the improved discharges from the 4m ovens, but may have arisen from a marginal increase in production rate from the 6m ovens, although there were no complaints regarding the visual appearance of discharge from the 6m ovens.

4.12.4 STRATEGY 6

To reduce the action limit from 1000°C to 600°C per shift after 6 months of successful operation.

In view of the degree of control which had been established, as shown in Fig. 56, it was agreed that such a change was practicable.

4.12.5 STRATEGY 7

To introduce the system of Carbonisation CuSum control to the 6m oven battery after its successful application on the 4m oven batteries.

The effect of this strategy was to produce very beneficial step changes in the Deposition CuSums for the two gauges in Llanwern village, but the effect was quite modest at the more distant gauges. The combination of Carbonisation CuSum control and improved grit arrestment gave deposition values at the nearby gauges which were within 50mg m⁻²d of their background values, as described in Chapter 2.

It is therefore clear that Carbonisation CuSum control represents a valuable aid towards process control at coke works, and should form an essential feature of Best Practicable Means at such works. The prevention of Grade 3 pushing emissions will simplify the subsequent application of any items of arrestment equipment considered necessary for further abatement of discharge emissions.

Some concern had originally been expressed that coke produced using the Carbonisation CuSum control technique would be less reactive than that made by traditional Western methods. Experience has shown such concern to be groundless, and there have been no indications of any adverse effect on iron production rates, or costs.

One other significant, but unexpected, benefit arose from the use of this method of control, related to the darkness of the emissions from the main chimneys on the 4m oven batteries. Dark emissions from the main chimneys arise when products of combustion migrate from the ovens, through cracks in the brickwork, into heating flues. Various methods have been developed to minimise such leakage, usually based on filling the cracks with a refractory powder. However, it was found in this instance that the increase in temperature of the heating flues, after removal of the blockages, caused a significant improvement in the visual appearance of the emissions, as measured by the Ringelmann scale(29), no doubt due to reduction in the size of the cracks by expansion of the brickwork.

4.13 THE EFFECT OF FUEL GAS CHANGES

An experiment to study the effect of fuel gas changes was made over a 5 week period on the 6m ovens, giving 105 values of the Carbonisation CuSum. For most of this time, blast furnace gas was used, but there were three short periods when a change to coke oven gas was made. Blast furnace gas is of lower calorific value, and the higher volumes of gas required lead to a better heat transfer, so firing by blast furnace gas was the preferred option.

By monitoring the effect of the changes on the Carbonisation CuSum during this period, the results for part of which are shown in Fig.58, it can be seen that each change to coke oven gas firing led to a severe transient reduction in flue temperature. This gave rise to Strategy 8.

4.13.1 STRATEGY 8

To ensure that in the works gas usage plan, the coke ovens had priority for blast furnace gas.

Investigations into the temperature reductions revealed a number of blockages in the coke oven gas feed lines, which were then cleared, thus minimising another area of process variance. This is a good example of the use of the Carbonisation CuSum as an investigational tool.

NOTE This evaluation was carried out by Mr. J.G.Isaac(52), and is included with his permission.

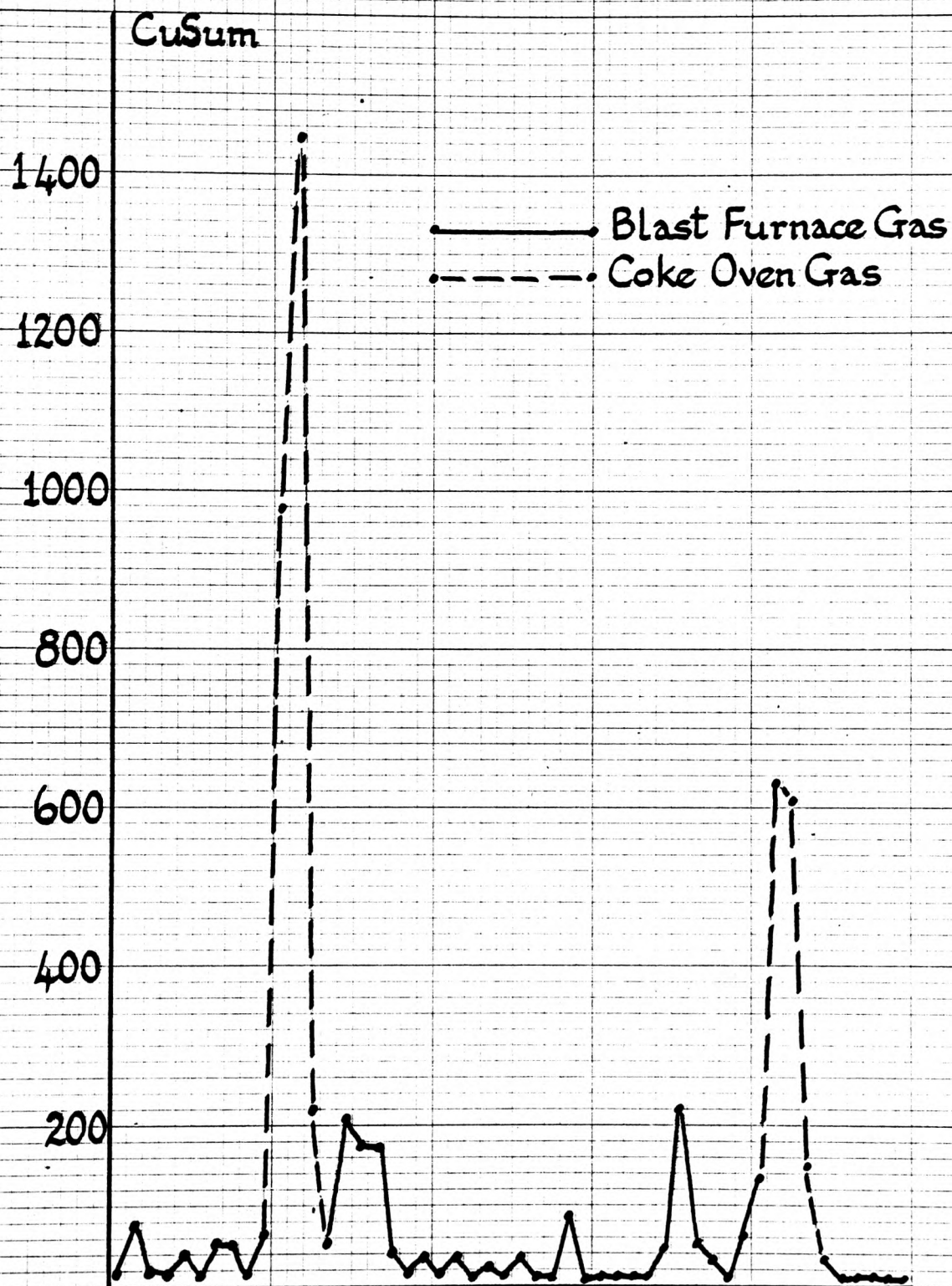


Fig.58
Effect Of Fuel Gas Changes On
Carbonisation CuSum

4.14 FLUE TEMPERATURE MEASUREMENT WITH A REGENERATIVE HEATING SYSTEM

Coke oven batteries employ a system of regenerators for heat recovery from combustion gases. The flow through the regenerators is reversed every 30 minutes, and from the moment of reversal the temperatures in the heating flues begin to fall. It is thus necessary to monitor heating flue temperatures at a consistent relative time, and it is usual for this to be done at 10 minutes after reversal. If taken at some other time, a correction should be made by reference to a cooling curve. Such curves are best determined experimentally for individual batteries, but typical curves have been published, as for example(39) in Fig. 59. This shows that for the period following 10 minutes after reversal, the rate of cooling is circa 4°C per minute.

The need for careful timing in these measurements can be illustrated by the effect on the Carbonisation CuSum of delays which are uncorrected. Assuming that all three routinely-monitored temperatures would be affected equally, and that the variations would be distributed equally above and below the operating curves, it can be shown that delays averaging 3-4 minutes would increase the CuSum sufficiently to trigger a reduction in the pushing schedule. Temperatures are measured manually with an optical pyrometer, and this illustrates the need for a most rigid discipline with regard to timing, which may be difficult to achieve in practice, and/or the careful use of cooling curves.

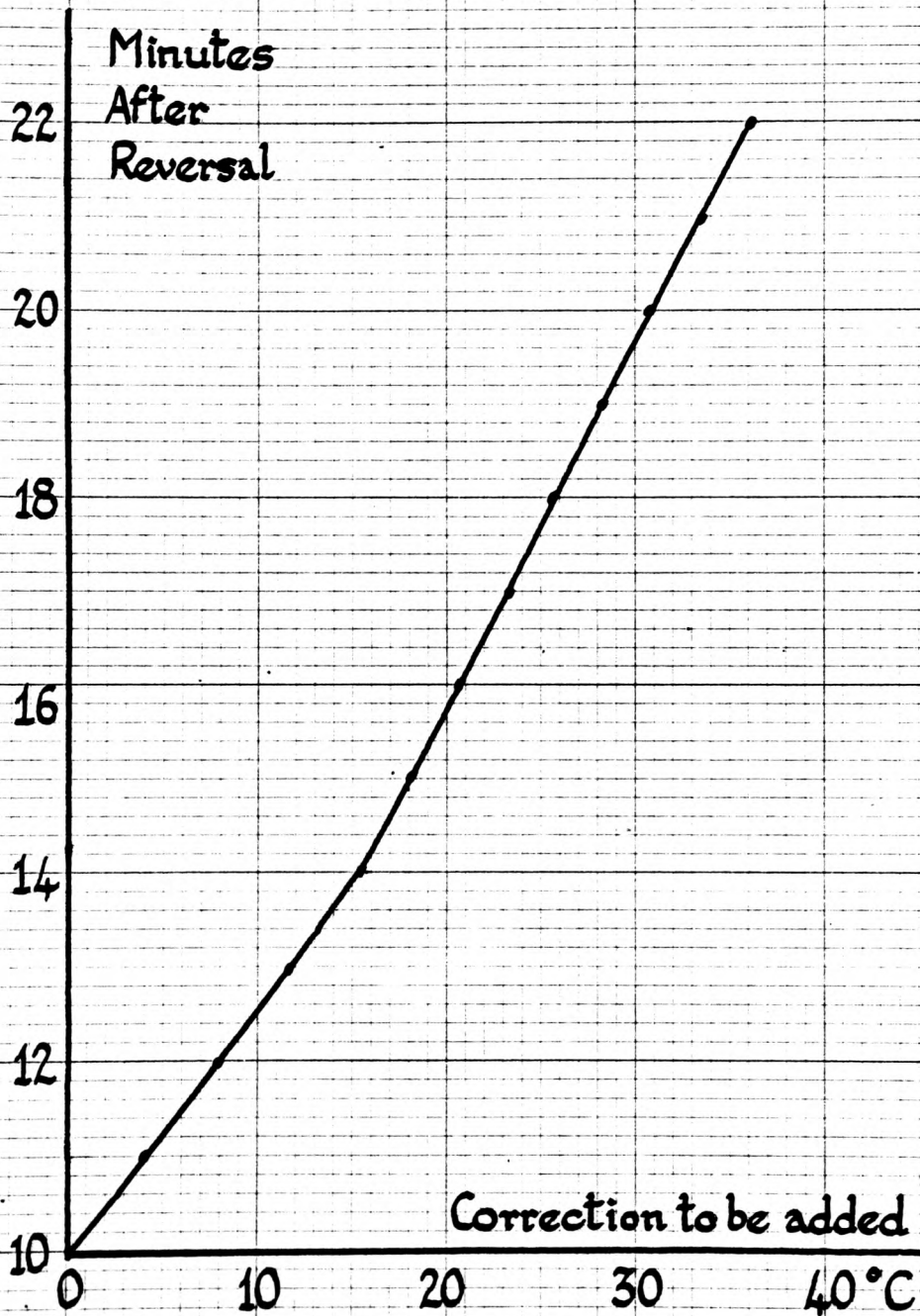


Fig. 59

A Cooling Curve For Use With
Regenerative Heating Systems

One practical problem has been observed in this area, relating to the induction of new carbonisation controllers, whereby the lack of familiarity with their duties caused delays in heating flue temperature measurements, which went undetected. The resultant CuSum values should have triggered a reduction in throughput, but there had been no records of poor emissions on oven discharges. Further investigations revealed the need to apply cooling curve corrections on a temporary basis, and the problem was overcome.

The effect of such minor uncorrected changes on the Carbonisation CuSum thus demonstrates the need for great care in monitoring the heating flues, and proves again the sensitivity of the system.

4.15 SUMMARY OF THE STRATEGIES ADOPTED

(a) 4m OVEN BATTERIES

1. To follow the revised operating curves by increasing the "Shift Average Temperature" target, i.e. by increasing the total heat input.
2. To follow the revised operating curves by extending the carbonisation period, and using less-elevated temperatures.
3. To maintain the Carbonisation CuSum below 1000°C per shift by increasing the total heat input, based on retrospective assessment of need.
4. To maintain the Carbonisation CuSum below 1000°C per shift by reducing the production schedule by one oven per day if the CuSum rose above 1000°C during any of the shifts on the previous day.
5. To prevent any increase in production schedule which would cause the Carbonisation CuSum to rise above 1000°C in subsequent shifts.
6. To reduce the action limit from 1000°C to 600°C per shift after six months of successful operation.

(b) 6m OVEN BATTERIES

7. To introduce the system of Carbonisation CuSum control to the 6m oven battery after its successful application on the 4m oven batteries.

(c) OVERALL

8. To ensure that, in the works gas usage plan, the coke ovens had priority for blast furnace gas.

4.16 A PRIORITY SYSTEM FOR RECOVERY OF "COOLER" OVENS

It was mentioned in section 4.10.2 that the economic benefit from the recovery of blocked flues could be determined, and justified the cost of the work to unblock them. For the most rapid return on this expenditure, it was necessary to establish a system of priorities to determine which oven flues had the poorest heat transfer. The information for this assessment was provided directly by the proforma used for calculation of the CuSum. The system of priority was based on preparing individual CuSums for each oven over a number of complete cycles of discharges, and selecting for attention those ovens showing the highest cumulative values. For ease of presentation, this information was shown in graphical form as in Fig. 60. There are many heating flues along both walls of an oven, and the next step was to select the actual flue(s) to be cleaned. This was done by measuring the actual temperature at each burner block, in what is termed a cross-wall survey.

The cleaning process involved demolition of a section of wall at the base of the heating flue, removal of any solids build-up, and reconstruction of the wall. This often led to temperature increases of 200°C in individual flues, and had a very positive effect in reducing local areas of under-carbonisation. As the blocked flues were recovered, the CuSums would reduce, allowing increases in the production schedule. The results shown in Fig. 56 were achieved while schedules were also being gradually increased.

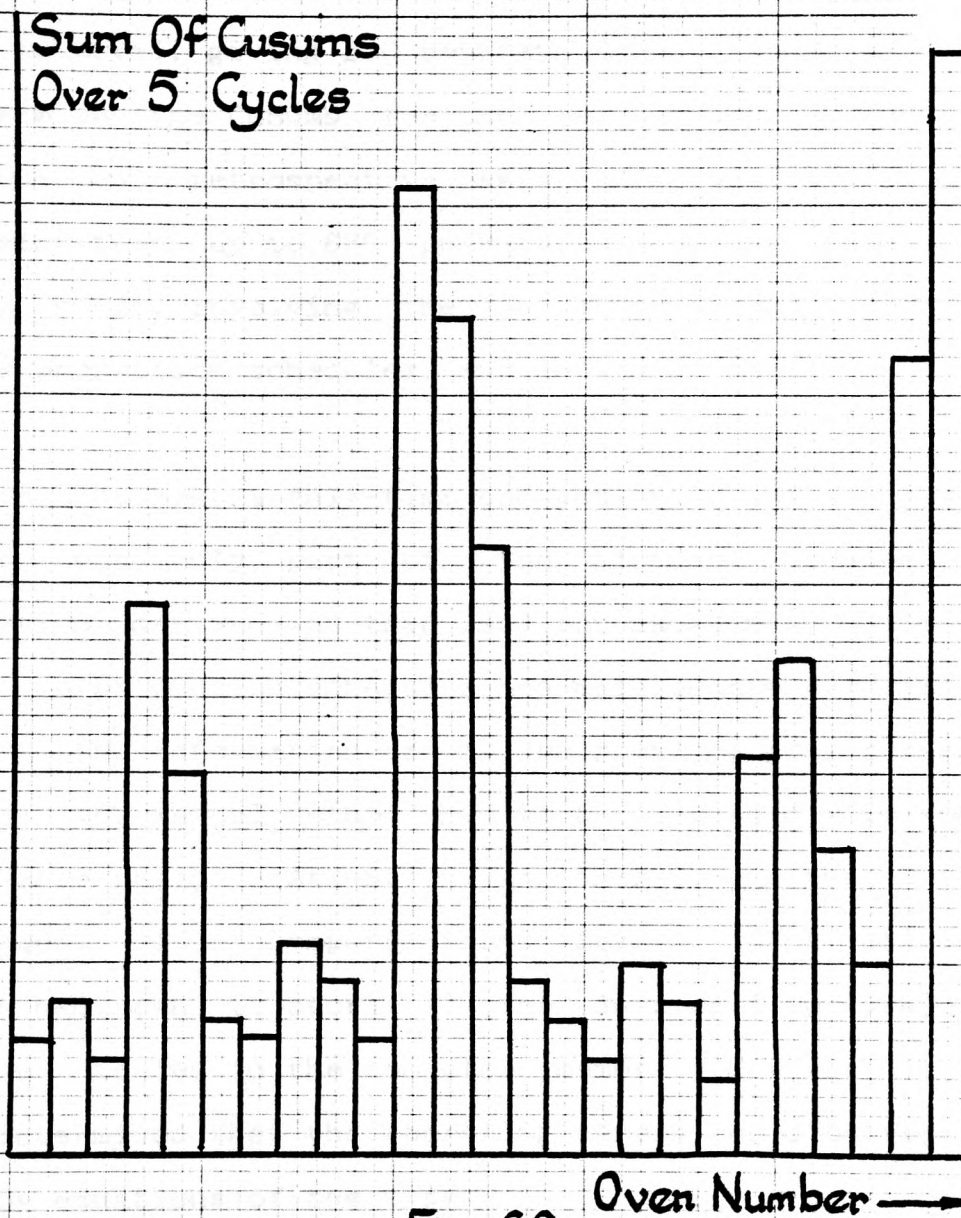


Fig. 60
Determination Of Ovens
Needing Priority Attention

4.17 THE DEVELOPMENT OF A COMPUTERISED SYSTEM

With the use of the Carbonisation CuSum system on both the 4m and 6m ovens, discharges could be as high as 70 per shift in total, giving 210 separate calculations per shift to determine the CuSums for the two plants. Since they were done on a retrospective basis, for the previous day, this meant that up to 630 calculations had to be done on the day shift, involving the use of prepared tables for various production schedules, and choice of fuel.

This became almost a full-time occupation in its own right, but it was only part of the picture, because the information derived was then used for management decision-making on production schedules and maintenance priorities. Clearly, the information had to be provided promptly each day, and the manual method had to be replaced with something more rapid. Attention was therefore given to the development of a computer-based method. The original concept had been to store all the data held on prepared "look-up" tables in the computer memory. However, it was then determined that the operating curves could be represented by equations of the type:-

$$\log K = \log T + n.\log P \quad (4.17.1)$$

where T = Heating Flue Temperature (K)

P = Carbonisation Period (h)

K = Constant

On the basis that the carbonisation period is defined by the operating schedule, the derived operating curves, when using coke oven gas, can be represented by:-

$$\text{RAMSIDE} \quad \log T = 3.5399 - 0.2857 \log P \quad (4.17.2)$$

$$\text{MIDDLE} \quad \log T = 3.5409 - 0.2797 \log P \quad (4.17.3)$$

$$\text{COKESIDE} \quad \log T = 3.5420 - 0.2740 \log P \quad (4.17.4)$$

In each case, if blast furnace gas is in use, the required operating temperature is reduced by 30°C.

By specifying the production schedule for each battery, and the type of fuel gas in use, it was thus straightforward to calculate the required flue temperature according to the derived operating curves, and the control procedures became much simplified. A programme for the calculations, using Acorn Atom Basic, was written by the author in April 1983, and adapted by B.S.C. Llanwern to run on a dedicated Pet microcomputer. Numerous extra features were subsequently incorporated, such as automatic lists printed for all negative deviations more than a given amount, and the selection of ovens for priority maintenance attention.

The programme can also be used to simulate the effect of proposed changes in schedule on the Carbonisation CuSum, and has demonstrated that the agreement of a maximum change of 1 oven per day (Strategy 4) is based on sound logic, since a rate of change of 1 oven per shift, would produce a change of more than 1000°C in the CuSum.

The computer is now used with other programmes, such as determination of priorities for oven door maintenance based on the degree of leakage, and the printouts can be passed directly to the department concerned for action.

In terms of information technology in coke ovens, the introduction of the microcomputer has been revolutionary, but it is still realised that the present system depends on double entry of control data. The monitored operating temperatures etc. are first entered on to plant log sheets, and they are then transferred to the computer the next day. The ultimate aim is for the data to be keyed in directly at the plant control room in real time, which would allow the development of the dynamic sequential Carbonisation CuSum system described in the following section.

4.18 A PROPOSED DYNAMIC SYSTEM OF CONTROL BASED ON THE CARBONISATION CUSUM

Examination of operating records indicates that the heating flue temperatures have a fairly random distribution around the operating curves. When the Carbonisation CuSum concept was developed on the 4m ovens at B.S.C. Llanwern, it was accumulated from circa 80 temperature measurements per shift. At the original limit of 1000°C per shift, this corresponds to an average negative deviation of 12.5°C per heating flue temperature measured.

On this basis, it is proposed that on other batteries, which may have different production schedules, and/or different heating flue temperature monitoring arrangements, the following relationship should apply for the initial introduction of Carbonisation CuSum control (which will be termed the Recovery Phase).

Upper	Ovens	Temps.	
CuSum	=	Discharged x Monitored x 12.5°C	(4.18.1)
Limit	per Shift	per Oven	

4.18.1 THE RECOVERY PHASE

The objective of the Recovery Phase is to set limits for the operating parameters that will prevent the onset of Grade 3 oven discharge emissions.

On the assumption that the recovery is obtained initially by reducing the production schedule, an important point is to know when the schedule can be increased, after remedial work, without exceeding the upper CuSum limit. In such cases, the following reasoning can be applied:-

- (a) The derived operating curves indicate that at design rates, a change in the schedule by one oven per day will change the required temperatures by circa 7°C .
- (b) Since only the "cooler" ovens will affect the CuSum, and assuming an equal distribution above and below the curves, this will correspond to 3.5°C per flue monitored, or circa 30% of the upper CuSum limit of 12.5°C per oven for a full shift.
- (c) This indicates that the schedule may only be increased by one oven per day without exceeding the upper CuSum limit, if the actual CuSum for the shift were no more than 70% of the upper limit. This leads to the generalised operating diagram shown in Fig. 61. Such a diagram would be suitable for sequential control of the carbonisation process in real time.

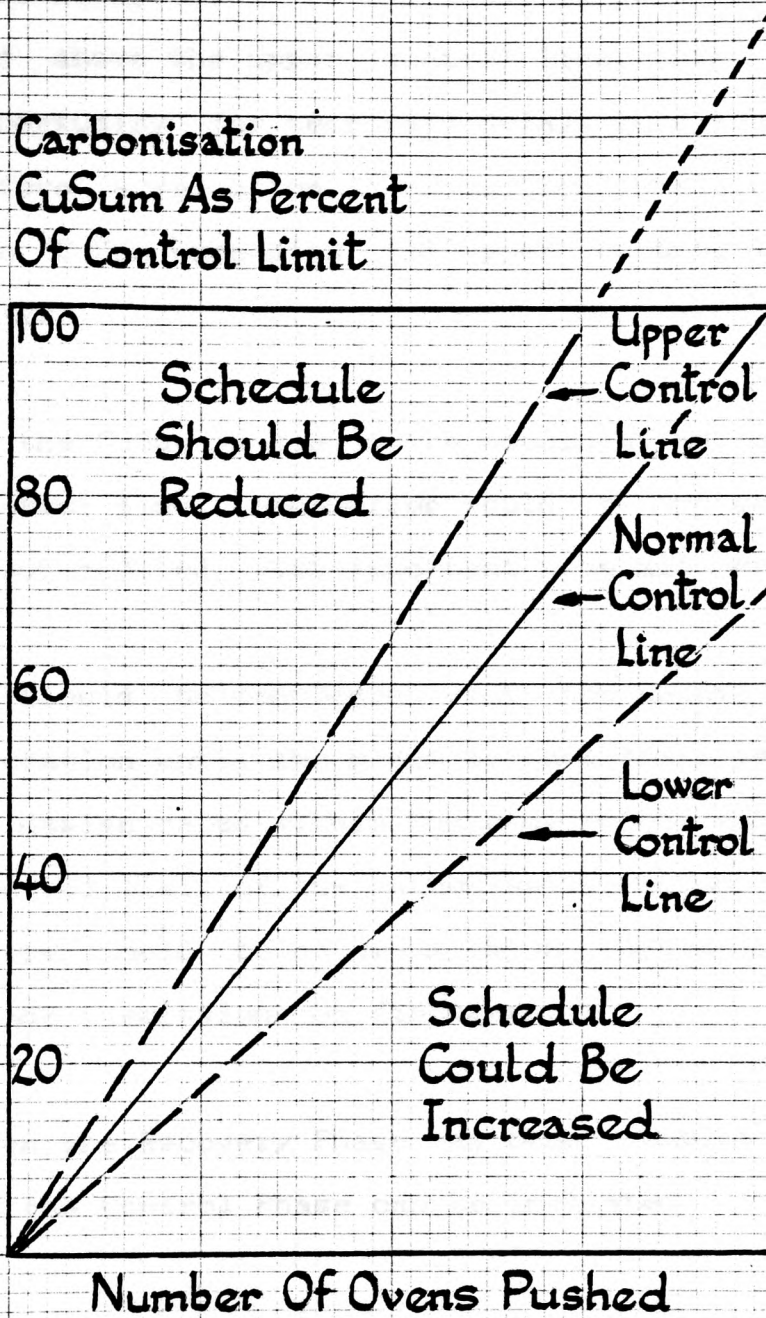


Fig. 61

General Operating Diagram
The Recovery Phase

(d) Calculation of the CuSum as a shift progresses would give a rapid assessment of whether or not operations were acceptable. If the CuSum is seen to be accumulating above the upper control line, this will give the opportunity for temporary delays in discharging ovens, before a reduction in production schedule is forced by the CuSum exceeding the upper control limit for the shift.

If the CuSum is seen to be accumulating below the lower control line, production could be increased, or heat input reduced, with important economic benefits.

(e) It should be considered that the Recovery Phase is in operation until the plant is once again able to produce at design rates within the constraints set by the upper control limit of the Carbonisation CuSum. In addition, there should be no ovens which regularly give rise to Grade 3 emissions on discharge.

When the Recovery Phase has been completed, transition to the Control Phase can be initiated.

4.18.2 THE CONTROL PHASE

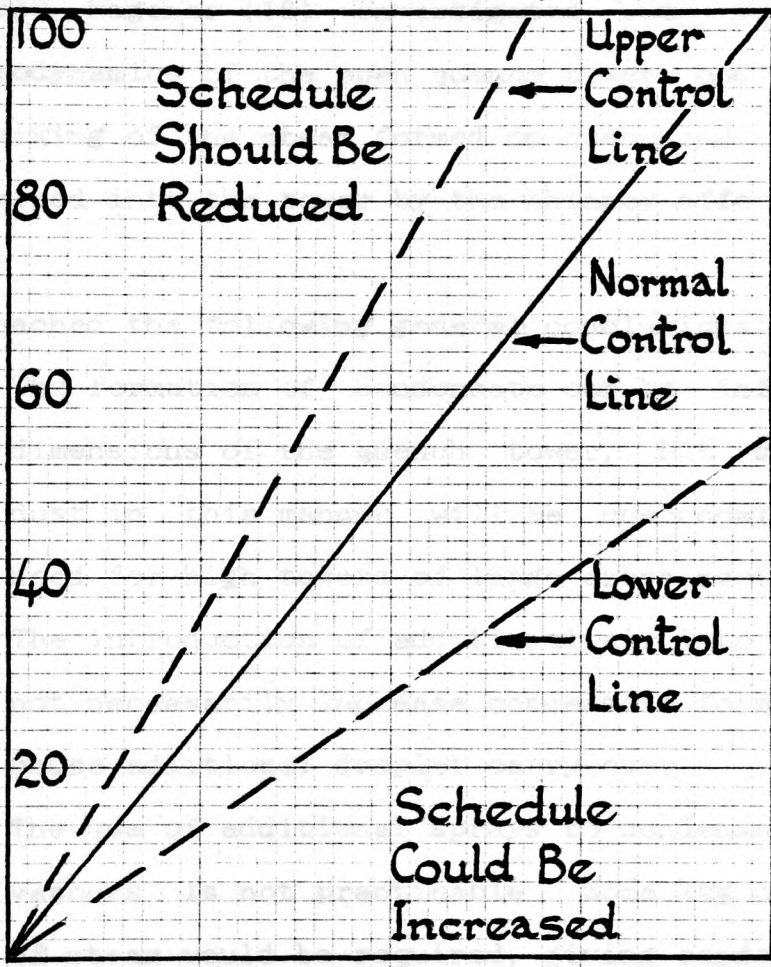
The objective of the Control Phase is to maintain limits for the operating parameters that will prevent the formation of Grade 3 emissions on discharge.

Based on the reduced limit for the CuSum agreed at B.S.C. Llanwern, the following reasoning can be applied:-

- (a) The upper limit of 600°C per shift on the 4m ovens corresponds to 7.5°C per flue temperature monitored.
- (b) The effect of a unit change in the daily schedule is unaltered at 3.5°C per flue temperature monitored. This corresponds to circa 45% of the upper limit given in (a) above.
- (c) This indicates that the production schedule may only be increased by one oven per day without exceeding the upper control limit, if the actual CuSum for the shift would be no more than 55% of the upper limit. This leads to the generalised operating diagram shown in Fig. 62. Such a diagram would be suitable for sequential control in real time.

Technology exists for automatic measurement of coke discharge temperature. Automatic calculation of the Carbonisation CuSum may be practicable, which could lead to significant improvements in quality of discharge emissions.

Carbonisation
CuSum As Percent
Of Control Limit



Number Of Ovens Pushed

Fig.62

General Operating Diagram
The Control Phase

CHAPTER 5

ELUTRIATION OF PARTICULATE MATTER FROM QUENCH TOWERS

5.1 THE EFFECT OF ARRESTMENT SYSTEMS ON GAS TEMPERATURE AND GAS COMPOSITION WITHIN A QUENCH TOWER

In 1960, Wagener (16) investigated some aspects of the thermodynamics of the open quench tower, and in particular, the mixing of the steam formed on quenching, with the gases entrained into the tower by the chimney effect.

He reached the following general conclusions:-

- (a) The formation of condensate can be influenced by the dimensions of the quench tower, but suppression of dust in this manner will be uneconomic, due to the need for high towers of large cross-section.
- (b) The introduction of additional air into the tower does not necessarily increase condensate formation, and may cause additional droplet carry-over.
- (c) The use of additional sprays to condense the emerging vapours is not practicable. Some 7kg of water per kg of steam would be required, giving condensate at 373K, which would require cooling.

The methods used in Wagener's study can be applied as below to indicate the changes in gas composition which arise from introducing arrestors. Peak temperatures recorded by Jackson and Waple (19) were 348K for the open tower, and 367K with arrestment. Fig. 63, derived from data in Perry (3), shows the variation with temperature in the amount of water vapour per kg of dry air, or the Humidity Ratio.

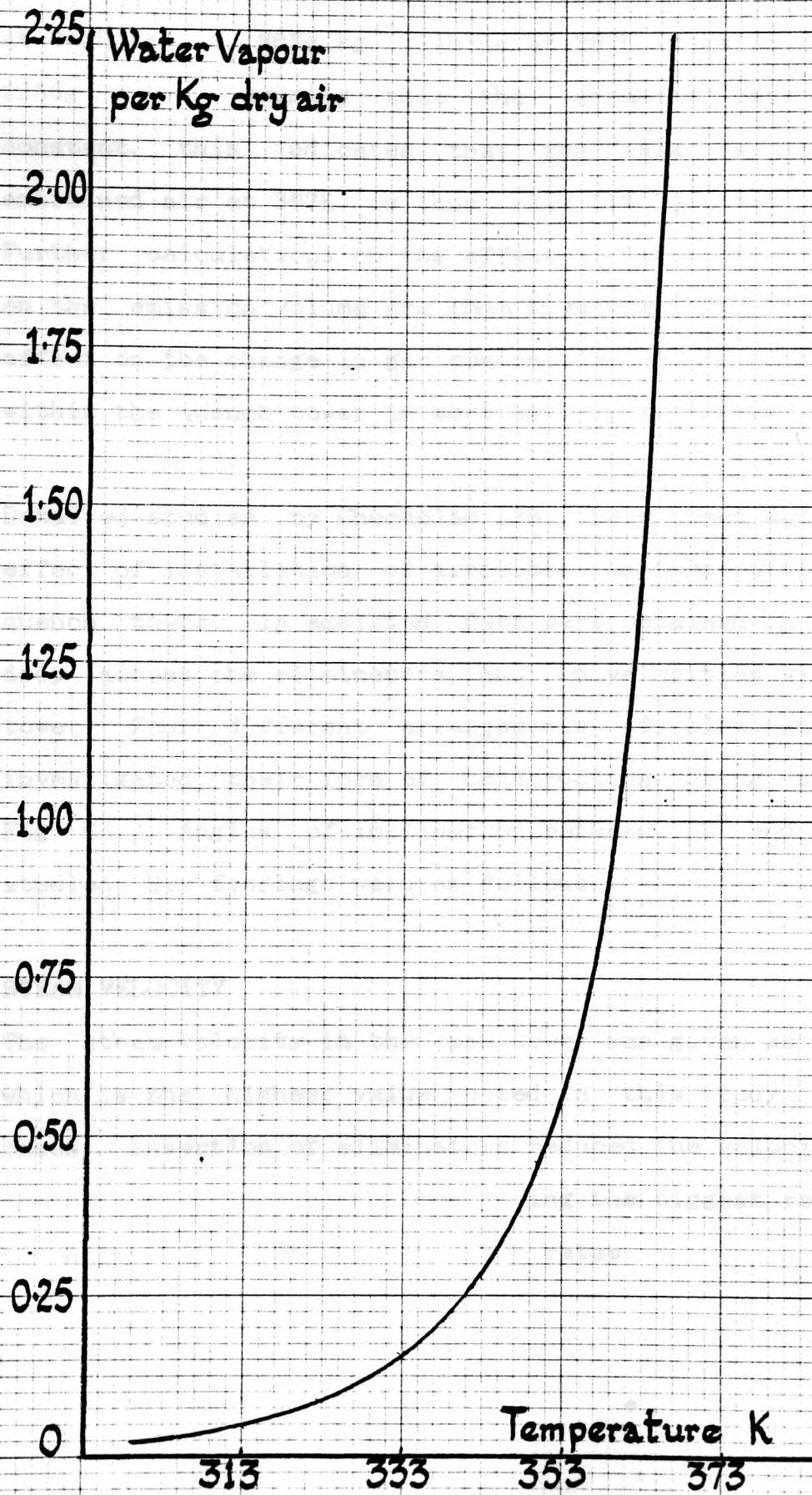


Fig.63 Humidity Ratios

At 348K this is 385g kg^{-1} , while at 367K it is in excess of 2250g kg^{-1} . Assuming that the steaming rate remains constant, this indicates that the relative amount of entrained air at 367K is thus only 17% of that at 348K. Further calculations on the effect of installing arrestors on the emission volume are given in section 6.4 (p 231-235) and the effect on the change in gas composition on other parameters within the quench tower in section 5.3. (p 193-198)

Detailed studies by Chocholac (36) have been made of the effect of installation of arrestors on temperatures in a quench tower. In addition, data were obtained on pressure drop across the eliminators, and on velocities within the tower. Four different arrangements of eliminator were investigated, their form of construction being shown in Fig. 64. Angles of inclination between 60° and 80° were studied. His findings were as follows:-

STEAM VELOCITY

The steam velocity in the open tower was given as 13m s^{-1} , which is the highest value noted in this study. In all cases, insertion of eliminators reduced the velocity, with the most efficient eliminator giving the biggest reduction, to under 10m s^{-1} at peak emission rates.

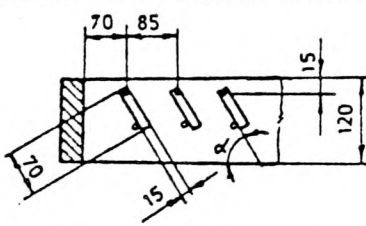
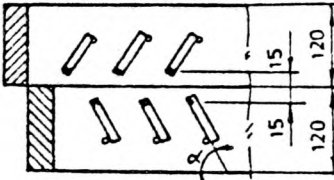
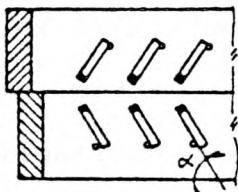
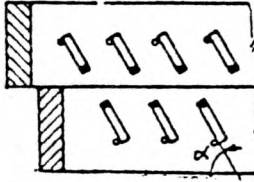
TYPE	FORM OF CONSTRUCTION	ANGLE
A		80
		70
		60
B		80
		70
		60
C		80
		70
		60
D		80
		70
		60

Fig. 64
 LOUVRE TYPES TESTED
 BY CHOCHOLAC (R)

STEAM TEMPERATURE

In the open tower, a peak temperature of 357K was recorded while quenching. This is the highest value noted in this study for an open tower, equivalent to a humidity ratio of 830g kg^{-1} of dry air.

NOTE

These temperatures are not strictly comparable with other published results, as they were measured below the eliminators rather than just before exit from the tower. Nevertheless, the insertion of eliminators caused an increase in temperature in all cases. With each of the arrangements tested, the inclination of 60° resulted in temperatures in excess of 373K for the majority of the first 60s of the quench period. The maximum temperature noted with various inclinations are shown in Fig. 65.

The work of Wagener (16) indicates that, to achieve a temperature of 373K beneath the eliminators, there must be exclusion of all entrained gases. To reach temperatures above 373K implies that the steam has been superheated by radiation from the red-hot coke, in the absence of entrained gases.

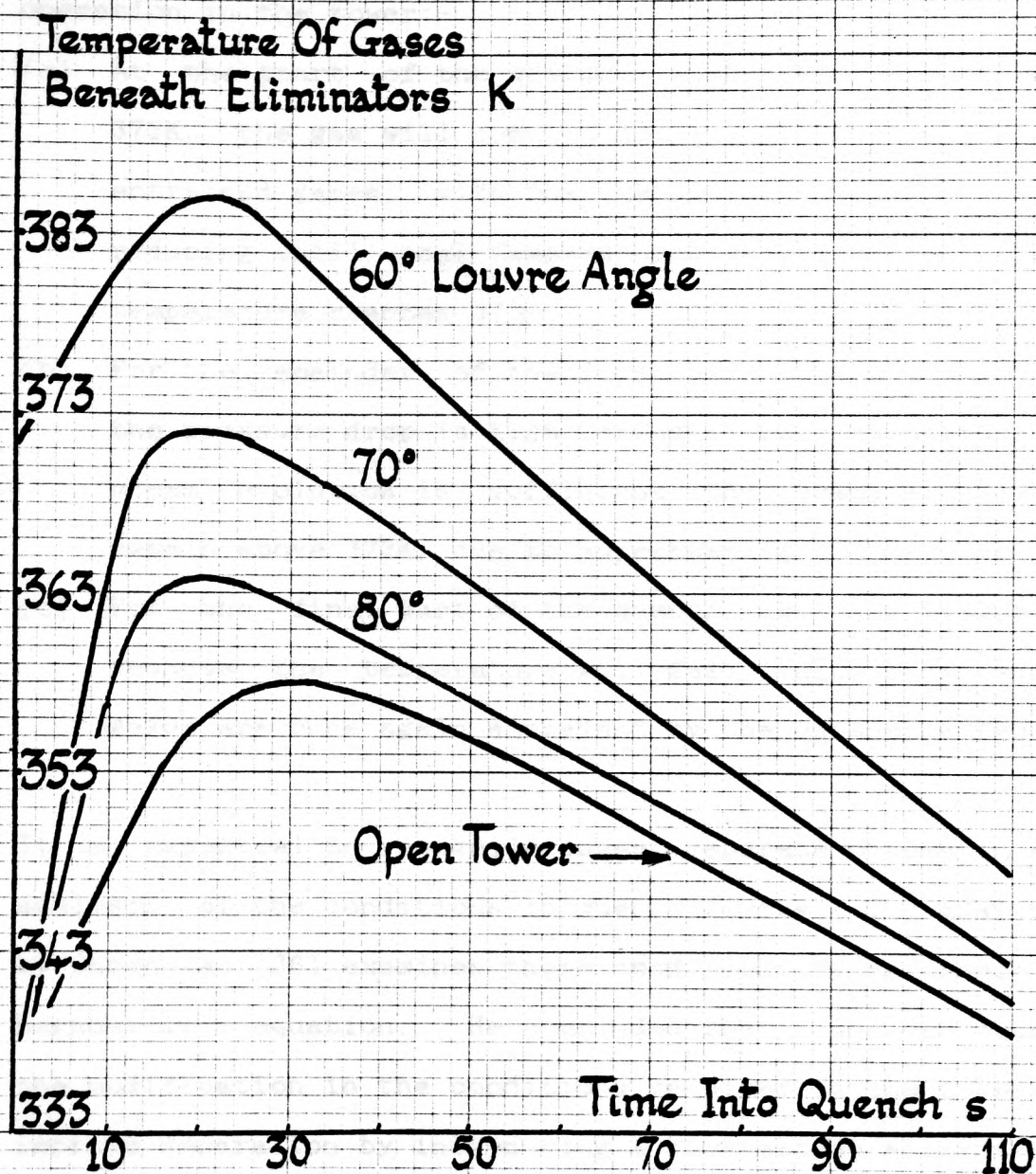


Fig. 65
Maximum Emission Temperature
Versus Louvre Angle (Chocholac)

Based on these two studies, it can be postulated that there will be in general, three separate phases to the quench operation in the tower:-

- (a) At the start of the quench, with temperatures below 373K, the gas will consist of a mixture of steam and entrained gases, with the amount of entrained gases reducing until peak temperatures are reached, or the temperature reaches 373K.
- (b) For the remainder of the first part of the quench, if the pressure drop is high enough, and the rate of steam evolution is sufficient, the temperature will remain above 373K, due to superheating by the coke.
- (c) For the final part of the quench, as steam evolution reduces, the temperature will fall below 373K, since gases are once again entrained by the chimney effect.

It is essential to recognise these separate phases in any analysis of the conditions in quench towers. The analysis by Chocholac (36) examines these conditions by reference to Bernouilli's equation. He concluded that "one can obtain the modification in the conditions required in the tower to improve separation by introducing a louvre-type eliminator, the pressure drop of which is greater than the potential energy of the tower without an eliminator".

This indicates that tall towers would require eliminators with a higher pressure drop than short towers in order to achieve the same change in gas composition.

5.2 THE CALCULATION OF TERMINAL SETTLING VELOCITY

The amount of particulate matter emitted from a quench tower depends on the velocity and viscosity of the carrier gas, the size of the particles, and their density. An understanding of the emission process can be derived from consideration of the equations which determine the terminal velocity of particles falling through a gas, starting with Stoke's Law:-

$$V_{ts} = \frac{2r^2 \rho_p g}{9 \mu} \quad (5.2.1)$$

where V_{ts} = terminal settling velocity
 r = particle radius
 ρ_p = particle density
 g = gravitational constant
 μ = dynamic viscosity of gas

In using Stoke's Law to predict terminal velocity, careful note must be made of its limitations. In particular, it applies to smooth small spheres of such size and density that the Reynolds Number (N_{Re}) is unity or less, falling through still air. This is because the coefficient of drag (C_D) is dependent on N_{Re} , which for a sphere may be defined as:-

$$N_{Re} = 2V \cdot r / \eta \quad (5.2.2)$$

where η = kinematic viscosity of gas

From equation (5.2.1), at 293K for a particle of density 1000kg m^{-3} one can derive, with particle radius in μm :-

$$V_{ts} = 12210 r^2 \text{ m s}^{-1} \quad (5.2.3)$$

Equation (5.2.2) can be re-written in the form:-

$$V_{ts} = \eta \cdot N_{Re} / 2r \quad (5.2.4)$$

Thus, combining equations (5.2.2) and (5.2.3), we get:-

$$\eta \cdot N_{Re} / 2r = 12210 r^2 \quad (5.2.5)$$

The limiting size for the applicability of Stokes Law can be found by putting $N_{Re}=1$, which then gives:-

$$r^3 = 6.126 \quad (5.2.6)$$

$$\text{thus } r = 1.83\mu\text{m}$$

$$\text{whence } V_{ts} = 4.1 \times 10^{-4} \text{ m s}^{-1} \text{ from equation (5.2.3).}$$

The majority of material emitted from quench towers is very much coarser than this, and hence Stokes Law will not apply. An alternative method for calculating terminal velocity is thus required, and such a method has been described by McDonald, University of Arizona (15), as follows.

The aerodynamic drag at the terminal velocity can be equated to the weight of a spherical particle to give:-

$$w = 0.5 \rho_m V_{ts}^2 C_d \pi r^2 \quad (5.2.7)$$

where ρ_m = density of medium

C_d = coefficient of drag

Difficulties arise in trying to solve for V , since C_d is also a function of V_{ts} through its dependence on N_{Re} , but one may make a direct solution from a plot of $C_d.N_{Re}^2$ against N_{Re} , since the term $C_d.N_{Re}^2$ does not contain V_{ts} .

$$C_d.N_{Re}^2 = 8w/(\pi \rho_m \cdot \eta^2) \quad (5.2.8)$$

Table 1 shows the data provided, and the method used is:

- (a) Compute $C_d.N_{Re}^2$ from the given parameters
- (b) Determine N_{Re} graphically
- (c) Determine V_{ts} by substitution for N_{Re} in equation (5.2.2).

For values of $C_d.N_{Re}^2 < 24$, that is $N_{Re} < 1$, Stokes Law will apply. However, this leads to particle sizes which are not significant in the present work. To assist in this study, the data in Table 23 have been incorporated into a computer programme, which can be found in Appendix 1.

Terminal velocities at 293K for coke particles of density 1000 kg m^{-3} falling in air have been determined by this method, and are shown in Fig. 66 together with the values which would be predicted by Stoke's Law if it were applicable in that region. It can be seen that

$C_d \cdot N_{Re}^2$	N_{Re}	C_d
24	1	24
64	2	16
140	4	8.8
230	6	6.4
420	10	4.2
1160	20	2.9
2880	40	1.8
5400	60	1.5
1.2×10^4	100	1.2
3.2	200	0.80
9.76	400	0.61
1.94×10^5	600	0.54
4.6	1000	0.46
1.64×10^6	2000	0.41
6.4	4000	0.40
1.44×10^7	6000	0.40
4.10	10000	0.41

Table 22

BASIC DATA FOR TERMINAL SETTLING VELOCITY SOLUTIONS

Terminal Settling
Velocity ms^{-1}
(Ambient Air)

293K

Log 2 Cycles x 2 Cycles

Graph Data Ref. 5922

Visual Level

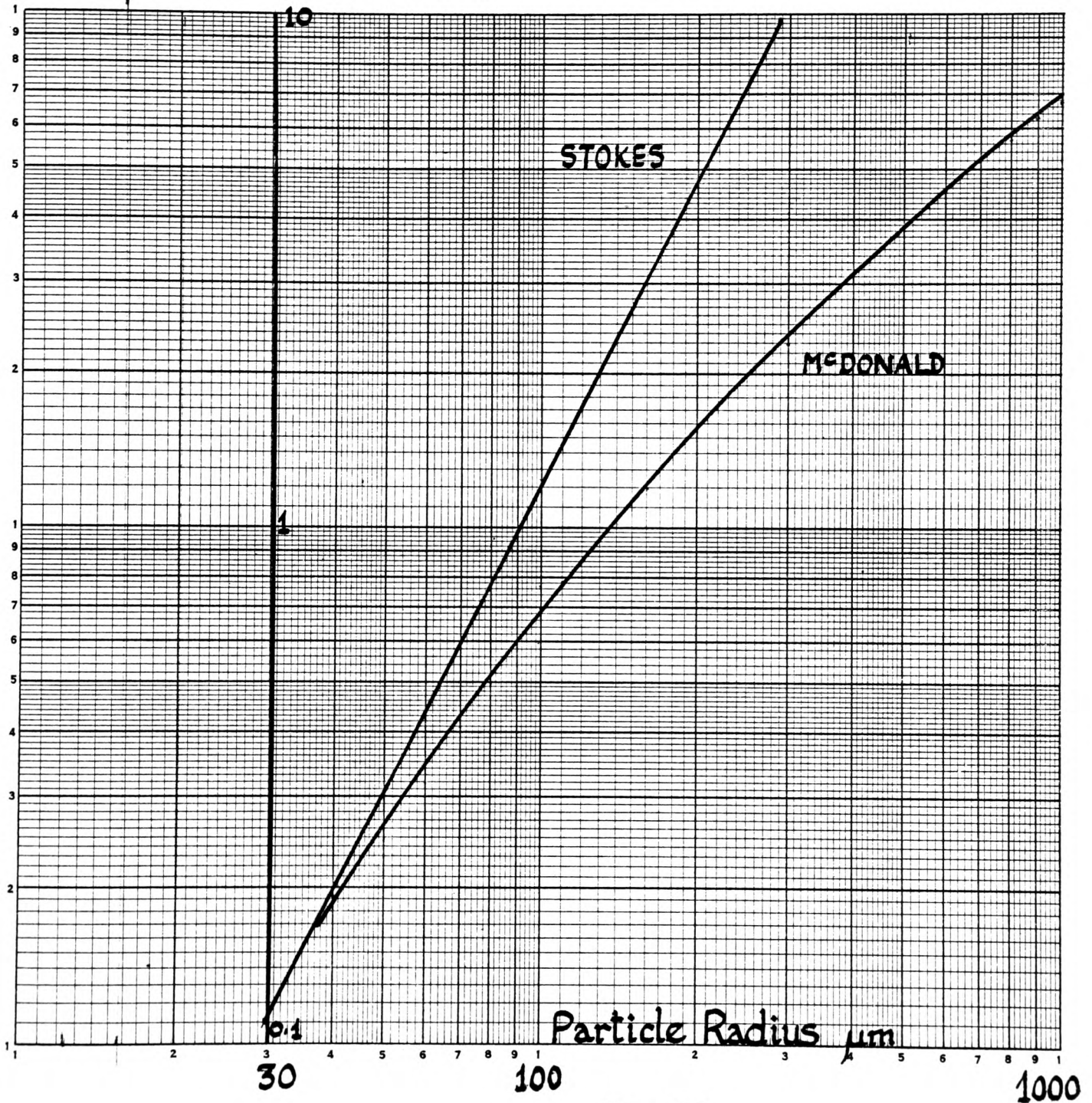


Fig. 66
Terminal Settling Velocity
Stokes and McDonald (R)

15

the McDonald values for particles above 30 μ m radius are less than the Stoke's Law values, and the divergence increases with increasing particle size. The McDonald method has been used for the remainder of this study, to examine conditions inside a quench tower, since he stated that the method is equally applicable to the prediction of terminal velocities of spheres moving through media other than air. In order to carry out these calculations, the changes of gas density and dynamic viscosity with temperature have to be quantified. This is done in the next section.

5.3 THE EFFECT OF GAS TEMPERATURE AND GAS COMPOSITION ON TERMINAL SETTLING VELOCITY

Wagener (16) considered that the conditions inside a quench tower could be calculated assuming an equilibrium between the steam produced on quenching, and the entrained air. Gas compositions have been calculated using his method based on partial pressures of air/water vapour mixtures from 273-373K at 1 standard atmosphere (1.013 MPa), and converted into density of the gas mixture. The results are shown in Fig. 67.

The dynamic viscosities of such gas mixtures were then calculated, using dynamic viscosity data in published tables(3), on a weighted basis. The results are shown in Fig. 68. It can be seen that the dynamic viscosity of the air/water vapour mixture falls rapidly over the range 343-373K. From the above sets of data, the corresponding values for kinematic viscosity have been calculated. The results are shown in Fig. 69.

Computations of terminal settling velocity have been made for particle sizes up to 1000 μ m, and temperatures over the range 293-383K. The results for a particle density of 1000kg m⁻³ are shown in Fig. 70. It can be seen that the terminal settling velocity increases significantly for temperatures above 340K. For temperatures above 373K, it has been assumed, based on the work of Chocholac (36), that

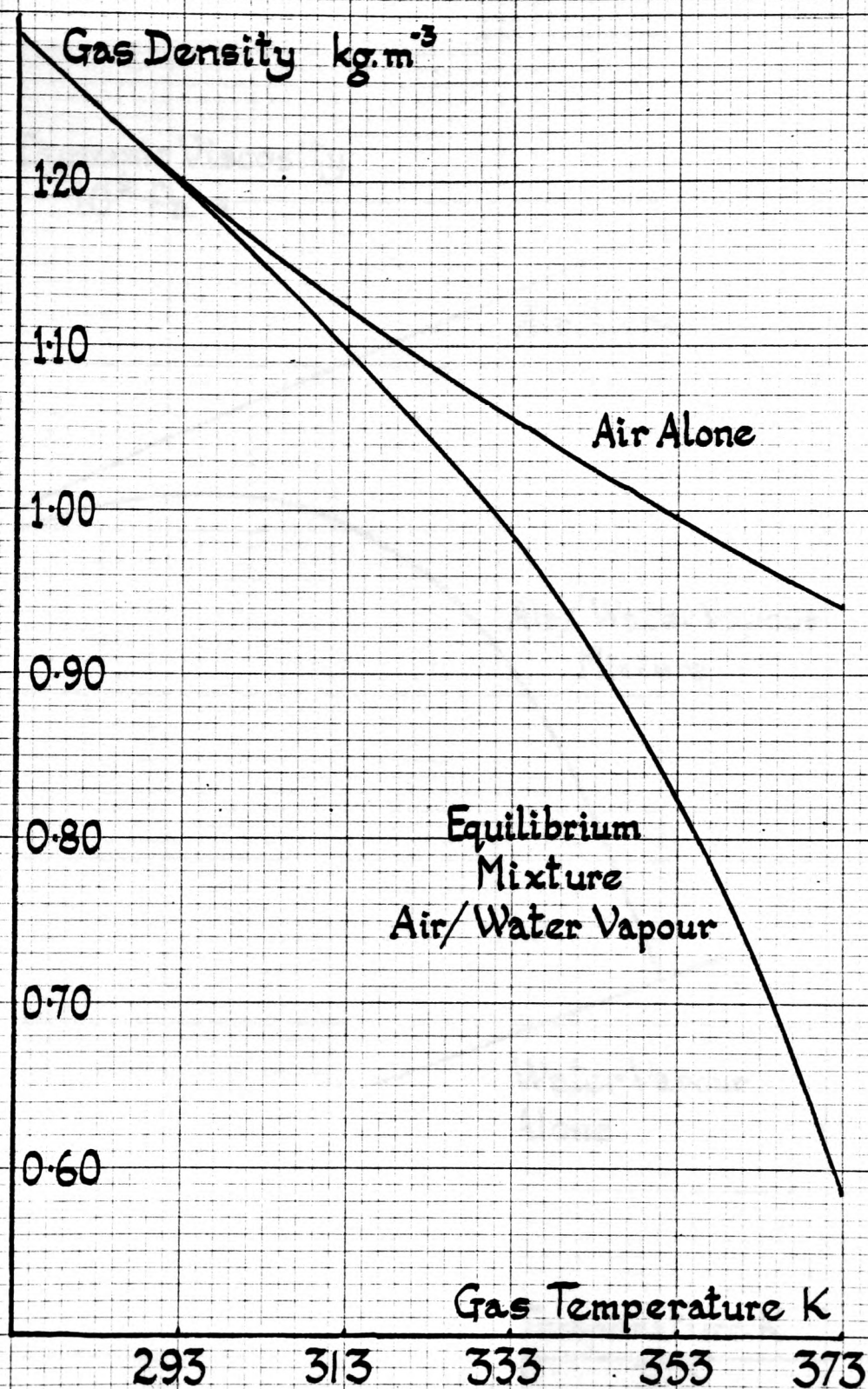


Fig. 67

Gas Density Versus Temperature
In Quench Tower (Wagener)

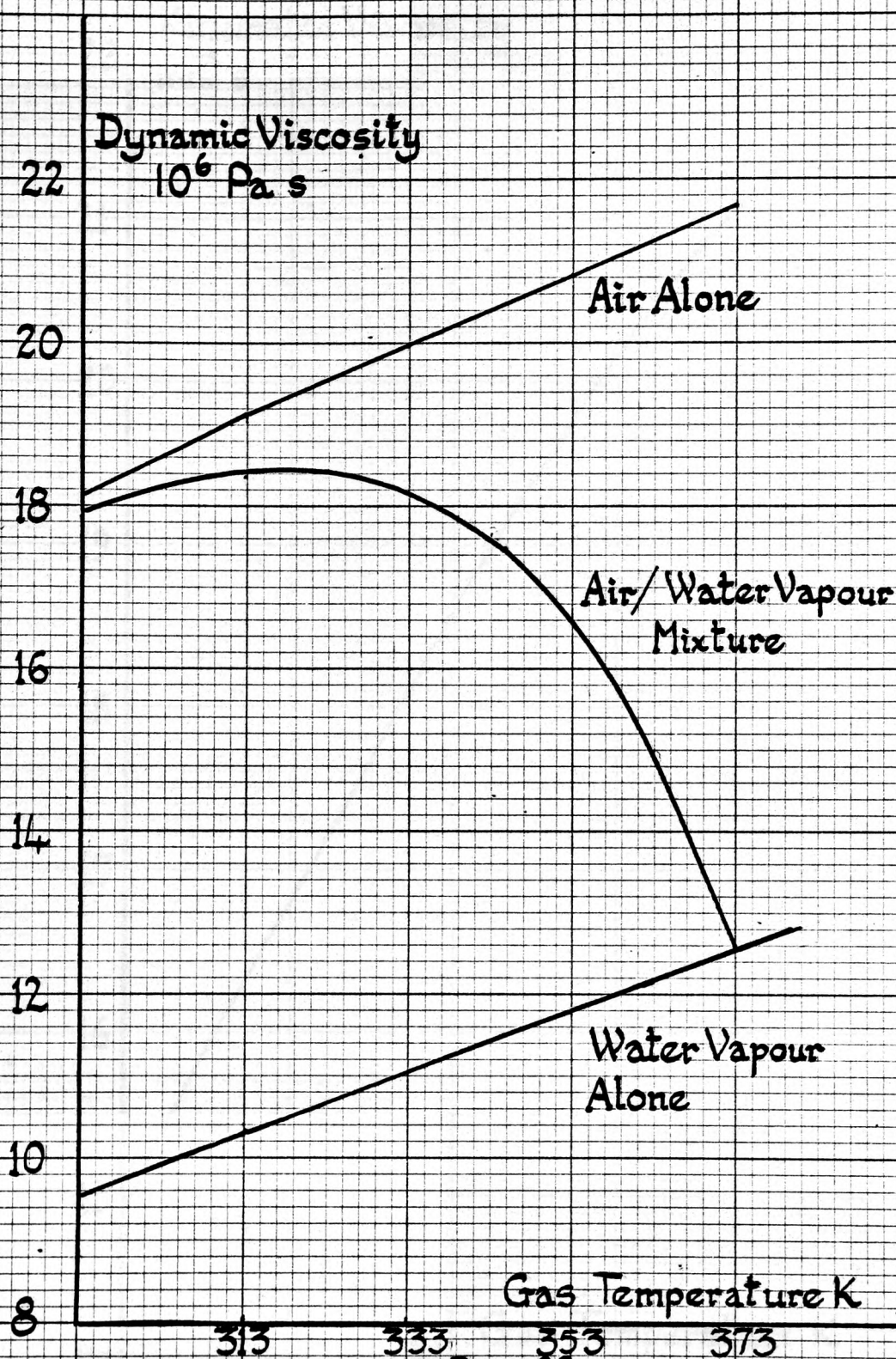


Fig. 68
Dynamic Viscosities For
Air/Water Vapour Mixtures

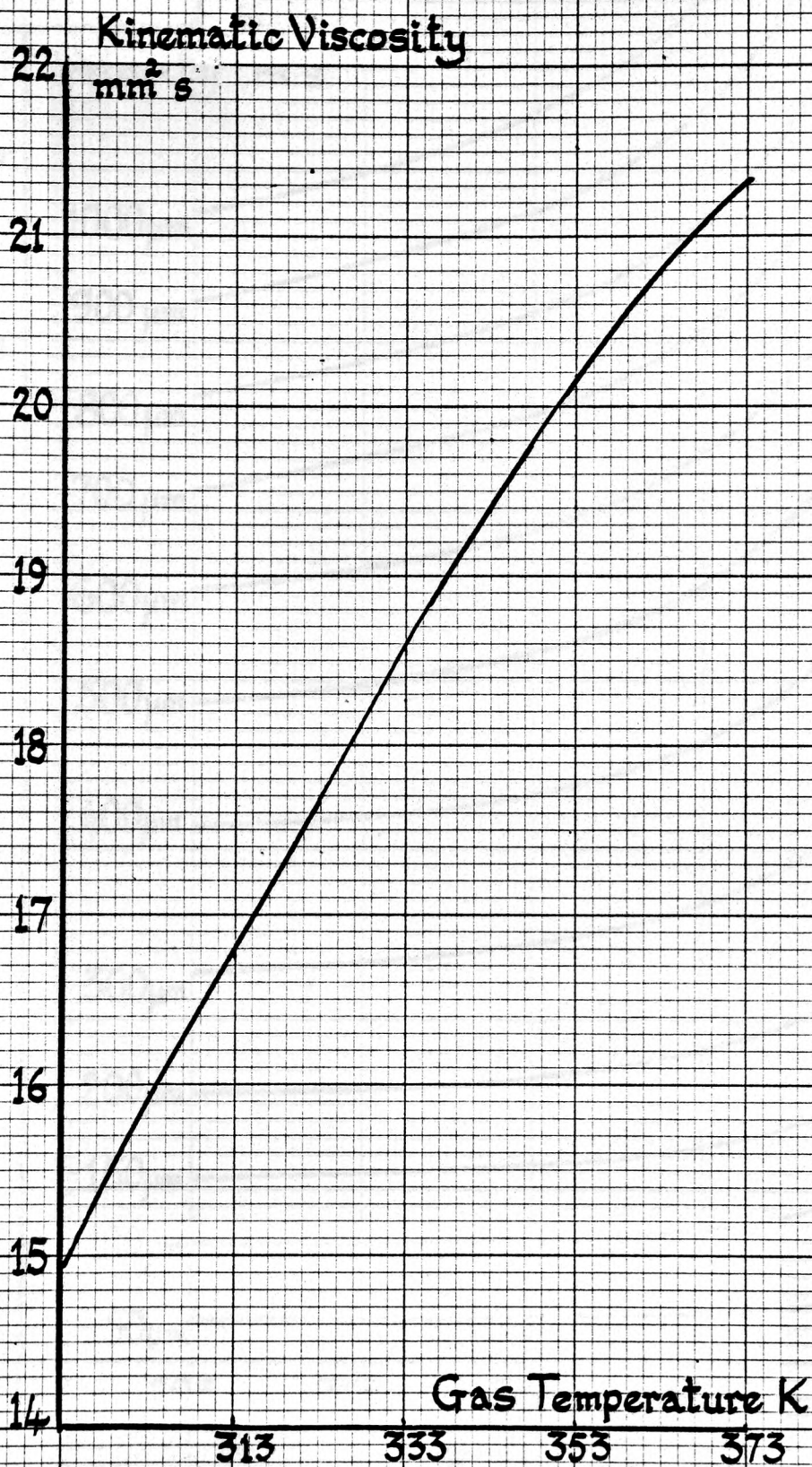


Fig. 69
Kinematic Viscosities For
Air/Water Vapour Mixtures

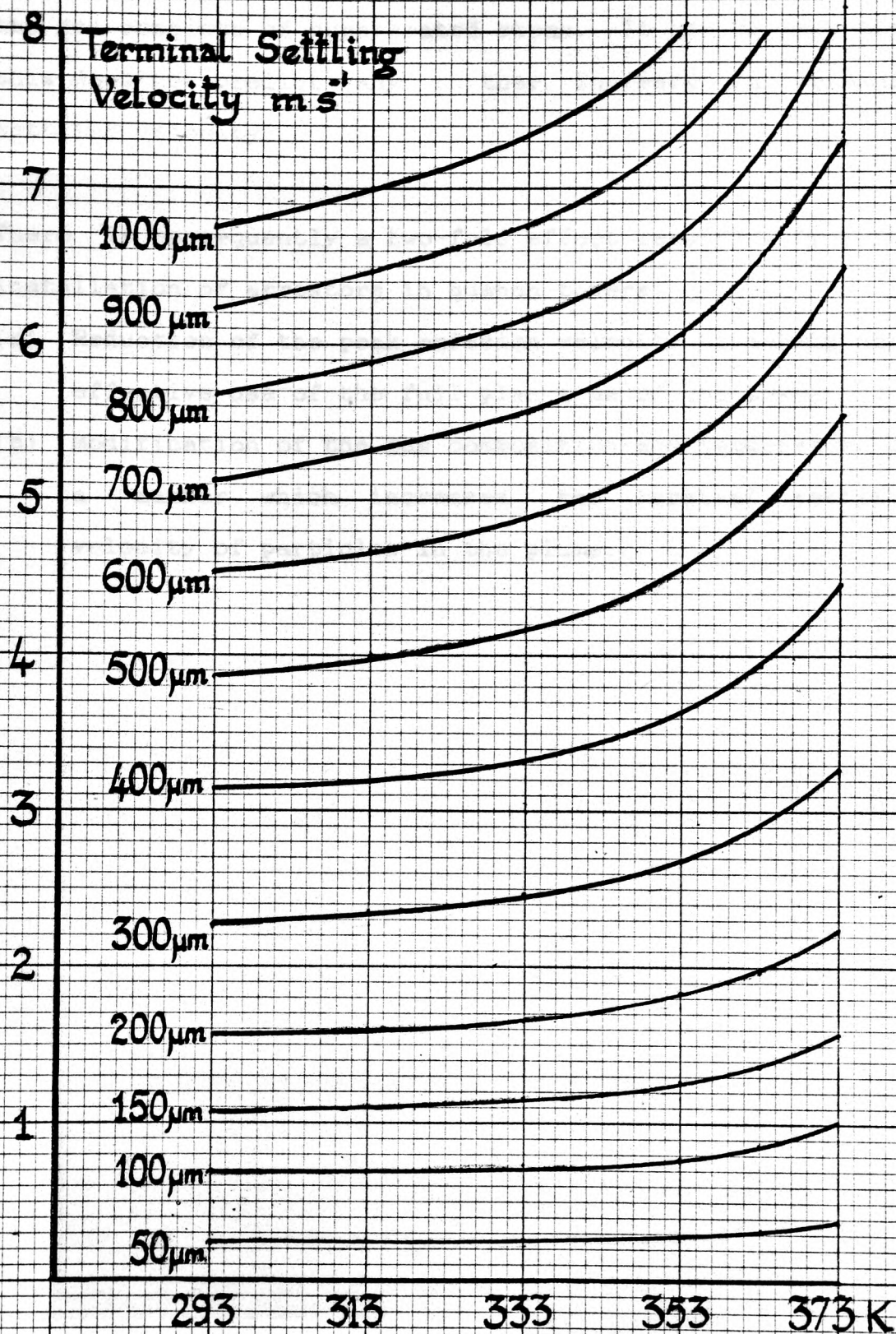


Fig 70

Terminal Settling Velocity In Quench Tower
Particle Density 1000 kg m^{-3}

the gas consists of superheated steam. It can be seen that this does not predict any further increase in terminal settling velocity.

There is consequently a two-fold effect resulting from the installation of arrestors in quench towers:

- (a) Reduction of the peak emission velocity by making more effective use of the full plan area of the tower,
- (b) Modification of the gas composition and temperature in a manner which increases the terminal settling velocity of particles in the plume.

5.4 THE APPARENT OR EFFECTIVE DENSITY OF PARTICLES EMITTED FROM QUENCH TOWERS

Information on the behaviour of non-spherical particles in terminal settling velocity problems is sparse. It has been suggested (40) that for such particles V_t may be as little as one third that of spherical particles. For this study, the approach taken has been to assume that the particles act as if they were spherical, while the anomalies are taken up by calculation of an "effective" density, which will be lower than the true density. The effective density has then been used both in evaluating behaviour within the tower, and in subsequent dispersion calculations.

The calculations so far in this study have a density of 1000kg m^{-3} . To estimate the effective density of particles in quench tower emissions, the results of Jackson and Waple (19) have been evaluated. Velocities and temperatures have been taken from their published graphs, and other parameters calculated as required. The maximum sizes of particle emitted in practice are then compared with Fig.70.

For the tower with arrestment, Jackson and Waple (19) reported that 5.6% was greater than $600\mu\text{m}$ diameter. Extrapolation of Fig. 29 indicates a top sizing of around $800\mu\text{m}$ diameter, or $400\mu\text{m}$ radius. Thus, the density can be no more than that which would allow particles of $400\mu\text{m}$ radius to reach the peak gas efflux velocity of 3.98m s^{-1} .

Fig. 70, based on a particle density of 1000kg m^{-3} , indicates that a particle of radius $390\mu\text{m}$ has a terminal settling velocity of 4m s^{-1} at 367K , and hence it can be concluded that the effective density is in the order of 1000kg m^{-3} .

For the open tower, the particle size distribution indicated that 9.4 - 10% was greater than $300\mu\text{m}$ radius(19). Extrapolation indicated a top sizing of around $500\mu\text{m}$ radius. Fig. 70 indicates that a particle of radius $600\mu\text{m}$ would have a terminal settling velocity equal to the efflux velocity of 5.3m s^{-1} at 348K . The effective density of the emitted particles has thus been taken provisionally as 1000kg m^{-3} .

On the basis of this density, the variation in maximum particle size with period into the quench can be estimated. The results are shown in Tables 23 and 24, and Fig. 71, for the central bay of the tower. These indicate how the installation of arrestors will reduce emission of the larger particles by modifying conditions within the tower, and hence will produce a finer particle size distribution for the emitted solids. The sharp peak for the open tower should be noted in particular, as this gives a further complication, considered in the following sections.

Time s	Temp K	V m s^{-1}	ρ kg m^{-3}	η $\text{mm}^2 \text{ s}$	Radius when $V = V_t$
10	328	3.95	1.012	18.15	479 μm
20	343	5.30	0.905	19.40	629
30	349	5.20	0.855	19.90	593
40	345	4.25	0.895	19.55	487
50	341	3.95	0.910	19.20	454
60	334	3.80	0.975	18.65	453
70	330	3.50	1.000	18.30	425
80	326	3.50	1.025	18.00	429
90	323	3.35	1.045	17.70	414
100	321	3.05	1.055	17.55	382
110	316	2.75	1.080	17.10	349
120	313	2.60	1.095	16.75	332
130	310	2.45	1.115	16.50	314
140	307	2.15	1.130	16.30	274
150	305	1.85	1.135	16.10	231
160	303	1.70	1.145	15.95	212
170	301	1.50	1.155	15.75	193
180	299	1.52	1.165	15.55	193

Table 23
 VARIATION IN SIZE OF PARTICLE EMITTED
 WITH TIME INTO QUENCH
 JACKSON AND WAPLE (19) - OPEN TOWER

Time s	Temp K	V m s ⁻¹	ρ kg m ⁻³	η mm ² s	Radius when V = V _t
10	331	2.45	0.995	18.40	300um
20	363	3.65	0.715	20.80	375
30	363	3.95	0.715	20.80	402
40	353	3.50	0.825	20.20	390
50	350	2.75	0.840	19.95	310
60	345	2.75	0.895	19.55	322
70	340	2.60	0.935	19.15	310
80	336	2.45	0.965	18.80	296
90	332	2.59	0.990	18.45	319
100	330	2.60	1.000	18.35	321
110	327	2.45	1.020	18.05	312
120	323	2.30	1.045	17.70	295
130	322	1.98	1.050	17.60	244
140	320	1.68	1.060	17.45	206
150	318	1.50	1.070	17.25	191
160	317	1.35	1.075	17.15	176
170	312	1.05	1.105	16.70	145
180	305	0.90	1.135	16.15	124

Table 24
 VARIATION IN SIZE OF PARTICLE EMITTED
 WITH TIME INTO QUENCH
 JACKSON AND WAPLE (19) - WITH ARRESTMENT

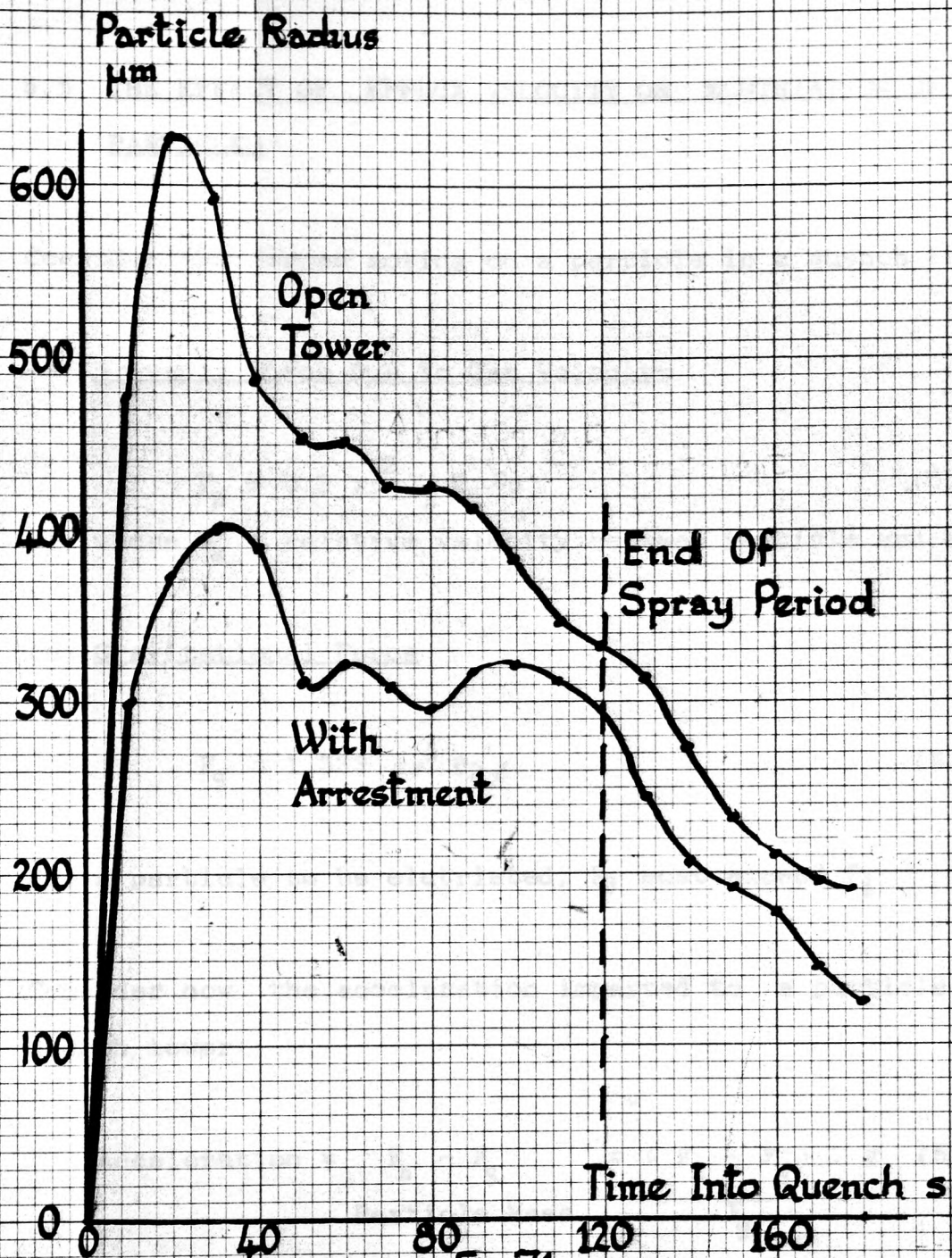


Fig.71
 Variation In Size Of Particle Emitted
 With Time Into Quench
 Jackson And Waple
 Particle Density 1000 kg m^{-3}

5.5 THE EFFECT OF EFFLUX VELOCITY ON ELUTRIATION OF COKE PARTICLES

Consider the forces acting on a particle in a quench tower:

(a) Bouyancy Force Due To Gas Velocity

$$F_B = 0.5 \pi r^2 V_R^2 \rho_m C_d \quad (5.5.1)$$

where V_R = relative velocity between particle and gas

(b) Gravitational Force

$$F_g = 1.333 \pi r^3 \rho_p g \quad (5.5.2)$$

For a particle to be elutriated, F_B must exceed F_g .

Consider now the acceleration imparted to a particle in a quench tower:-

$$\text{Acceleration} = \frac{F_B - F_g}{\text{Particle Mass}} = \frac{(F_B - F_g)}{F_g} \cdot g \quad (5.5.3)$$

Now since acceleration = dv/dt , the upward velocity of a particle of given radius can be obtained by integration of the above equation. This has been done by a computer programme which calculates V_R at time intervals of 0.001s, the value of C_d being obtained from the previous McDonald programme. The results are shown in Fig.72, where it can be seen that the particle will then approach asymptotically a

Temperature 348K
Density 1000 kg m^{-3}

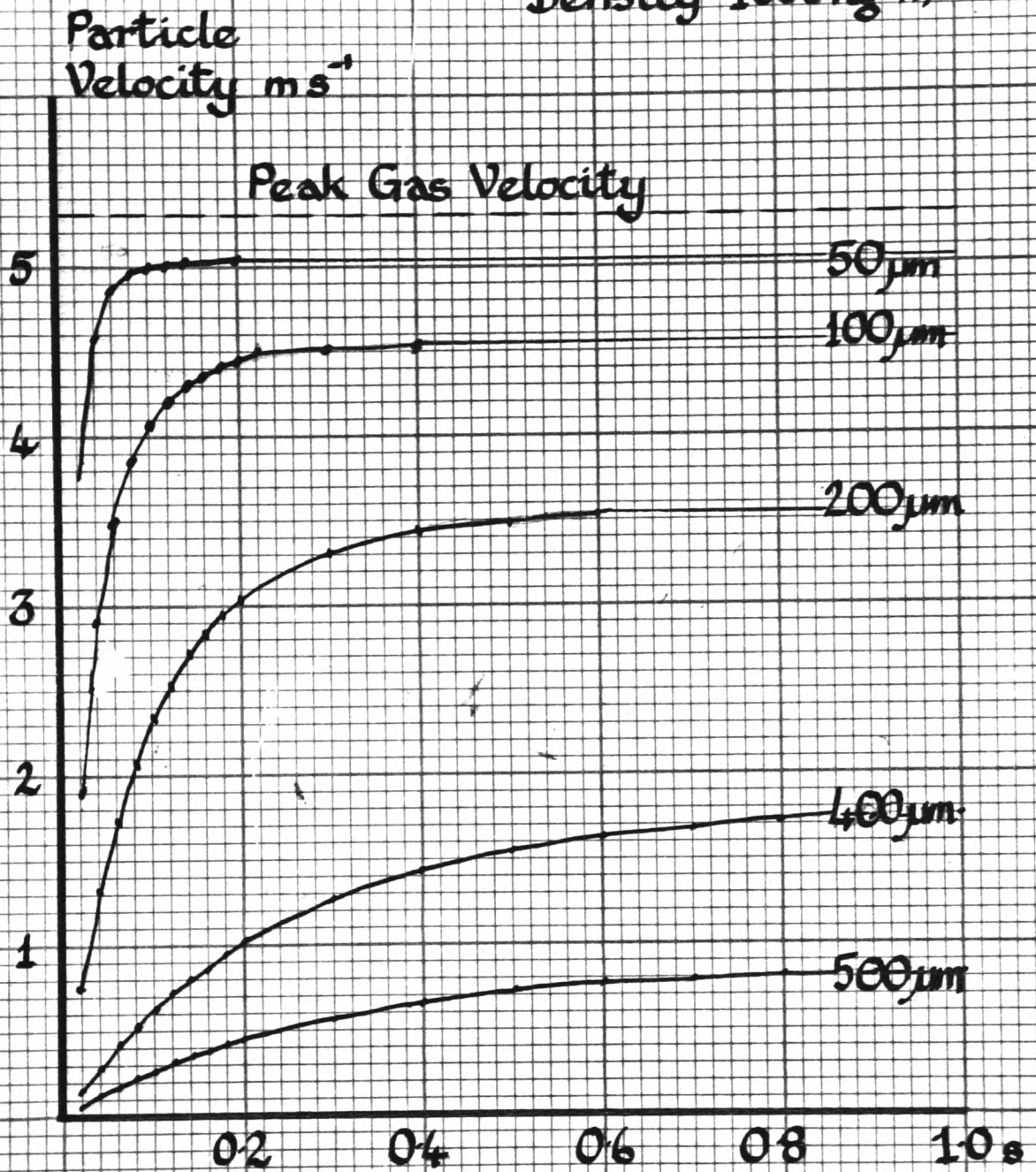


Fig. 72

Time Needed To Reach Final Upward Velocity
Jackson and Waple - Open Tower

velocity V_n , the net upward velocity, such that for each particle size:-

$$V_n = V_{\text{Efflux}} - V_{\text{Terminal}} \quad (5.5.4)$$

For the majority of the emission, it can be considered that particles travelling upwards in a quench tower will reach their terminal velocities within 1s, and the finest particles within less than 0.1s. However, for particles whose terminal velocities are close to the peak efflux velocity, V_n may not be sufficient to allow their escape from the tower during the short peak of the efflux velocity.

The low values of V_n for the largest particles suggest that relatively unsophisticated upper cleaning sprays should be effective in quench towers, since the largest potential targets would be virtually stationary.

5.6 THE TRANSIT TIME AVAILABLE FOR LARGER PARTICLES IN QUENCH TOWER EMISSIONS

The theoretical maximum size of particle that could be elutriated from a quench tower would be that for which the terminal settling velocity equals the peak efflux velocity. However, such a particle would have zero net upward velocity, and hence in practice would not be emitted. Therefore, it can be concluded that the maximum size elutriated will be lower than that predicted from the peak efflux velocity.

Fig. 71 indicates that, for the open tower studied by Jackson and Waple (19), the efflux velocity peak extends over about 12s, while for the tower with arrestment it is wider, covering say 20s. Thus, a particle close to the predicted size limit for the open tower would have no more than 12s in which to travel from the coke car to the top, a distance of 8-9m. The practical maximum size of particle to escape would thus have a terminal settling velocity of circa 0.7 m s^{-1} less than that predicted. For the tower with arrestment, the reduction would be circa 0.4 m s^{-1} .

Since the value of 1000 kg m^{-3} for effective particle density was based on correlation with particle sizes emitted in practice, the effect of the transit time correction is to indicate that the effective density may be lower. If the transit time correction is applied to the open tower, a terminal settling velocity of 4.6 m s^{-1} would correspond to a

particle size of $520\mu\text{m}$, and for the tower with arrestment, a terminal settling velocity of 3.4m s^{-1} would correspond to a particle size of $350\mu\text{m}$. Neither of these are sufficiently different from the extrapolated top sizes found in practice for the provisional estimate of effective density to be changed.

The transit time correction is probably more significant in tall (high velocity) towers, such as that studied by Fullerton (26). With a tower height of 30.5m , the transit distance above the sprays would be approx. 24m , which could lead to maximum values of terminal settling velocity some 2m s^{-1} less than the peak gas velocity of 11m s^{-1} . Based on a particle size distribution with 1% in the range $600\text{--}1500\mu\text{m}$ radius, the predicted particle size of $1250\mu\text{m}$ for a corrected efflux velocity of 9m s^{-1} at 344K gives further tentative confirmation of an effective particle density in the order of 1000kg m^{-3} , as shown in Fig.73.

The principle of elutriation can also be applied to water droplets, which can be considered as smooth spheres of density 1000kg m^{-3} . Few detailed results have been published, but the work of Portchmouth (7), on a 28.6m high open quench tower indicates a maximum radius for emitted drops of $325\text{--}375\mu\text{m}$ with an exit velocity of 4.5m s^{-1} at 339K , for the start of the quench. Allowing for the transit period in the same manner as for Fullerton above gives a reasonable agreement between Fig. 70 and the published maximum particle sizes of emitted droplets.

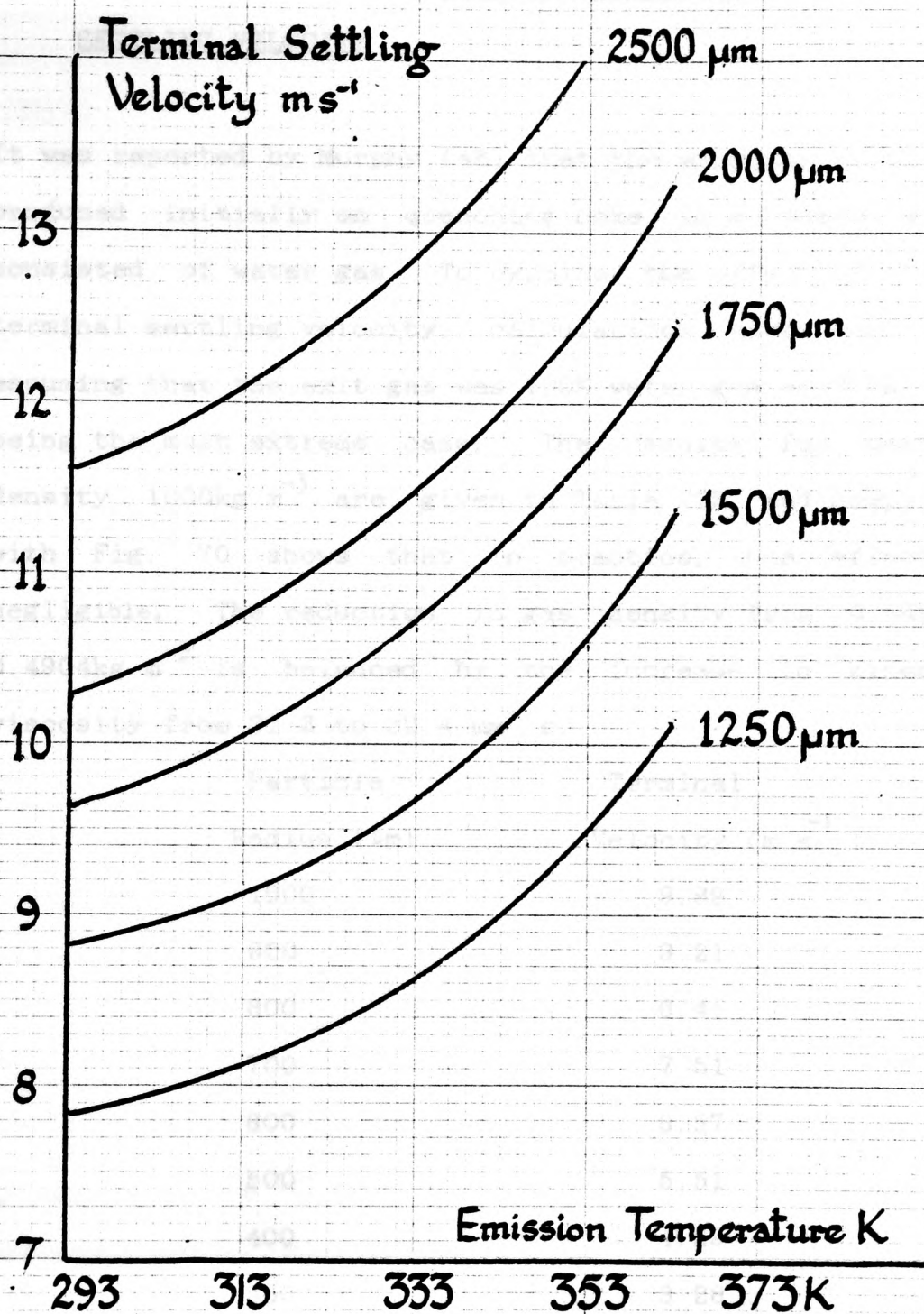


Fig. 73

Terminal Settling Velocities In Quench Tower
Particle Density 1000 kg m^{-3}
High Range

5.7 THE EFFECT OF THE WATER GAS REACTION ON TERMINAL SETTLING VELOCITY

It was reported by Murphy (48) that the majority of the gas produced initially on quenching coke in a sealed system consisted of water gas. To examine the effect of this on terminal settling velocity, calculations have been made assuming that the exit gas was 100% water gas at 373K, this being the most extreme case. The results for particle density 1000kg m^{-3} are given in Table 25, and comparison with Fig. 70 shows that in practice, the effect is negligible. The reduction in gas density from 0.5864 to 0.4904kg m^{-3} is balanced by the increase in kinematic viscosity from 21.3 to $32.4\text{ mm}^2\text{ s}^{-1}$.

Particle Radius (μm)	Terminal Velocity (m s^{-1})
1000	9.99
900	9.21
800	8.41
700	7.51
600	6.57
500	5.51
400	4.29
300	3.28
200	2.10
100	0.88

Table 25

TERMINAL SETTLING VELOCITIES IN WATER GAS AT 373K

CHAPTER 6

FACTORS AFFECTING THE RATE OF STEAM EMISSION FROM QUENCH TOWERS

6.1 THE THEORY OF NATURAL DRAUGHT QUENCH TOWERS

An open quench tower, by analogy with a natural draught cooling tower (30), operates at a gas flow where the available draught is balanced by the system resistance.

The available draught is given by the product $H_T \Delta \rho$, where H_T is the tower height, and $\Delta \rho$ is the density difference between the emitted gases and the ambient air. The system resistance to gasflow is expressed in terms of velocity head pressure, given by $\rho u^2 / 2g$.

The gas flow equation is thus:-

$$H_T \cdot \Delta \rho = N \cdot \rho u^2 / 2g \quad (6.1.1)$$

$$\text{or } H_T \Delta \rho \cdot g = 0.5 N \rho u^2 \quad N \text{ m}^{-2} \quad (6.1.2)$$

In practice, N is greater than 1 for open towers, due to the presence of water droplets formed by condensation.

The variation of N with emission temperature can be investigated using the results of Chocholac (36) for a 25m high open tower. Equilibrium data are shown in Table 26 and Fig. 74, and clearly show the expected reduction in N with increase in emission temperature. Extrapolation to 373K

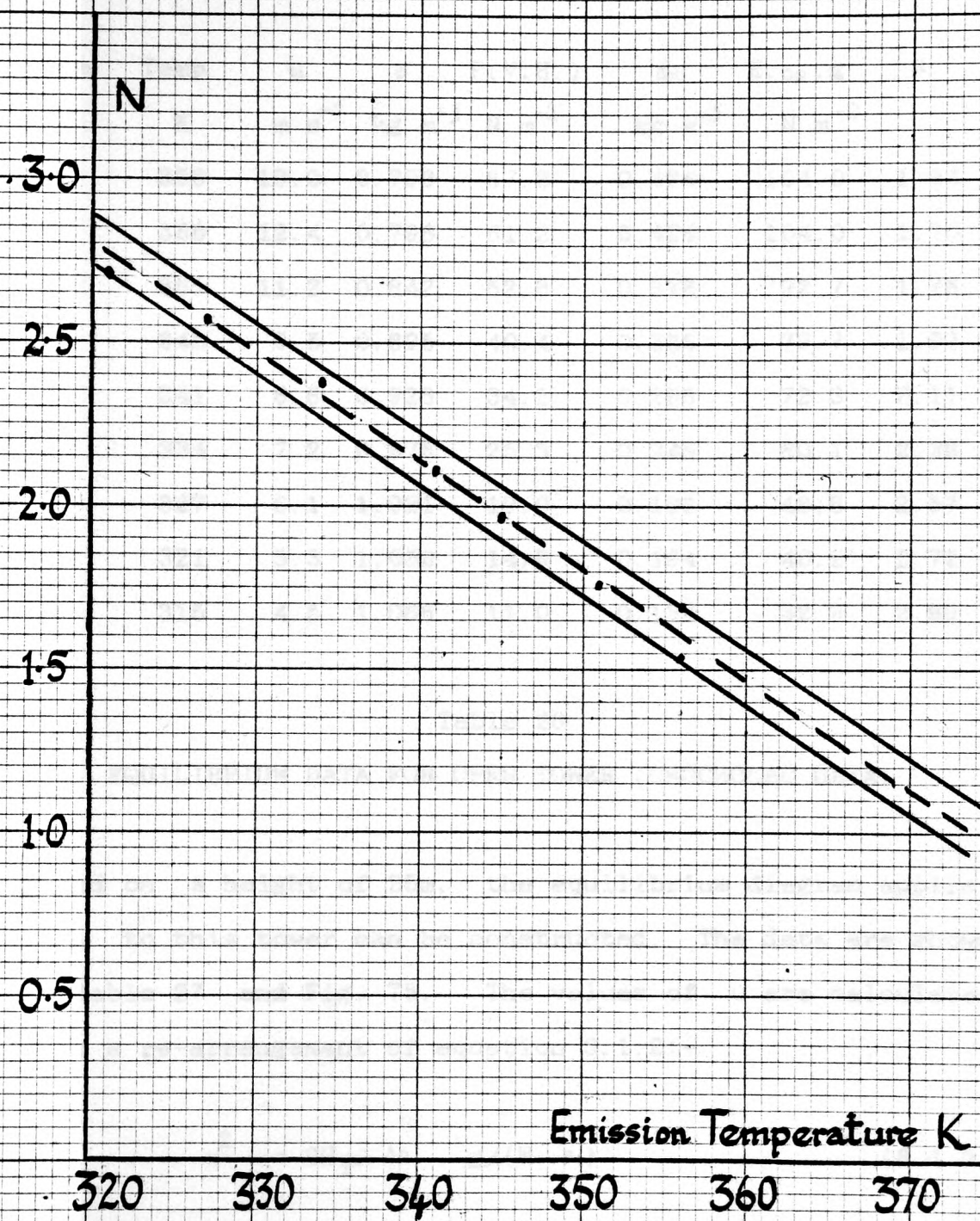


Fig. 74
Equilibrium Data For Open Tower
[Chocholac]

indicates a value of $N=1$, in the absence of condensation.

Time	Temp	u	ρ	P(V.H.)	$\Delta\rho$	$H \cdot \Delta\rho \cdot g$	N
s	K	m s^{-1}	kg m^{-3}	N m^{-2}	kg m^{-3}	N m^{-2}	
20	356	13.0	0.796	67.3	0.424	104.0	1.54
40	356	12.4	0.796	61.2	0.424	104.0	1.70
60	351	11.2	0.842	52.8	0.378	92.7	1.76
80	345	9.5	0.895	40.4	0.325	79.7	1.97
100	341	8.6	0.925	34.2	0.295	72.3	2.11
120	334	7.2	0.975	25.3	0.245	60.1	2.38
140	327	6.1	1.021	19.0	0.199	48.8	2.57
160	321	5.3	1.056	14.8	0.164	40.2	2.72
180	315	4.5	1.086	11.0	0.134	32.9	2.99

Table 26

EQUILIBRIUM DATA FOR OPEN TOWER (CHOCHOLAC DATA)

Based on a height of 25m, the equilibrium diagram applicable to this tower can be constructed. The data are shown in Table 27 and Fig. 75. The values of u are calculated from a re-arrangement of equation 6.1.2:-

$$u^2 = 2H_T \cdot \Delta\rho \cdot g / (N \cdot \rho) \quad (6.1.3)$$

- (a) The driving force, or tower draught, is first found from $(H_T \cdot \Delta\rho \cdot g)$ in N m^{-2} , represented by curve AB.
- (b) Division of the driving force by the value of N from Fig. 74 gives the velocity head pressure curve CB

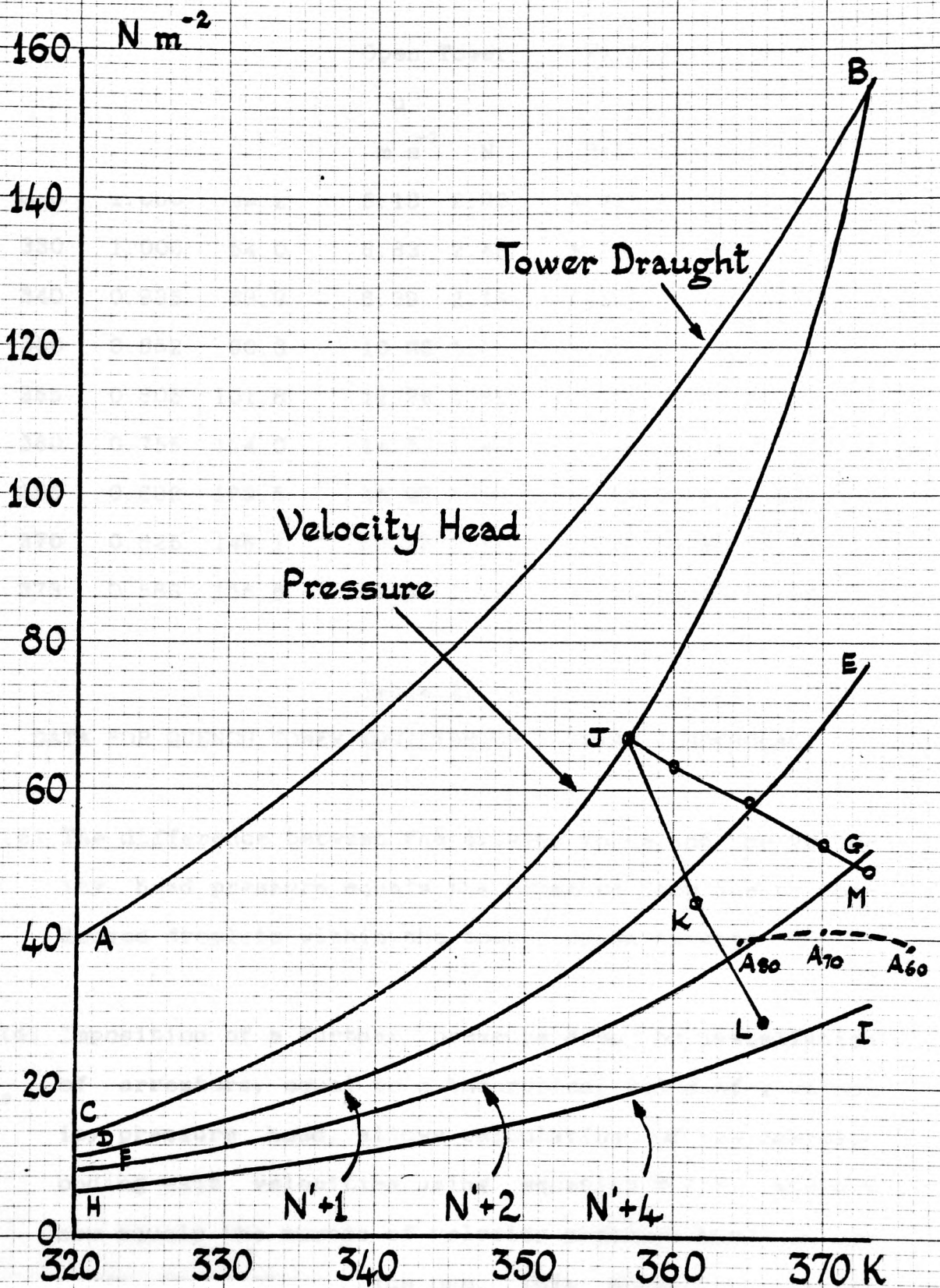


Fig. 75

Quench Tower Equilibrium Diagram
[Chocholac Data]

Temp	ρ	Draught	Open Tower		With Arrestment		
			u		u m s		
			$m s^{-1}$	N	$N+1$	$N+2$	$N+4$
K	$kg m^{-3}$	$N m^{-2}$					
320	1.060	39.2	5.13	2.80	4.41	3.92	3.30
330	1.000	54.0	6.63	2.46	5.59	4.92	4.09
340	0.935	69.9	8.39	2.14	6.90	6.01	4.93
350	0.852	90.3	10.82	1.81	8.68	7.46	6.04
355	0.805	101.8	12.38	1.65	9.77	8.32	6.69
360	0.755	114.0	14.33	1.47	11.06	9.33	7.43
365	0.692	129.5	16.97	1.30	12.76	10.65	8.40
370	0.625	146.1	20.25	1.14	14.78	12.20	9.54
373	0.586	155.5	23.03	1.00	16.29	13.30	10.30

Table 27

DATA FOR QUENCH TOWER EQUILIBRIUM DIAGRAM (CHOCHOLAC)

- (c) The difference between the driving force and the velocity head pressure equals the pressure drop due to condensed droplets within the tower, shown hatched.
- (d) Imposition of a further pressure drop, by installation of arrestors, equal to a theoretical value of 1 velocity pressure head, allows calculation of the corresponding exit velocities using equation 6.1.3, where N now equals the number of velocity pressure heads at any given temperature, plus one. This gives the line DE, marked $N+1$ on the diagram, and similar calculations have also been done to give lines for $N+2$ and $N+4$, shown by FG and HI respectively.

Based on the geometry of the arrestors, shown in Fig.64, it can be seen that with configuration A, the single row arrestors will occupy 15% of the area of the tower exit even when mounted in the vertical plane, while the double row will occupy 30%. The pressure drop on insertion of the arrestors will thus consist of two components:-

- (a) that due to reduction in area of the tower exit,
- (b) that due to the angle of the arrestors.

Consider first the peak emission condition for the open tower. Let a single row arrestor be inserted occupying 15% of the available area, and let the reduction in emission rate which ensues be entirely a reduction in entrained air flow. At 357K, the density is 0.787 kg m^{-3} , and the humidity ratio is 0.745. Thus for $x \text{ kg s}^{-1}$ of dry air there will be $0.745x \text{ kg s}^{-1}$ of water vapour, giving a mass emission of $1.745x \text{ kg s}^{-1}$, and an emission volume of $2.22 \text{ m}^3 \text{ s}^{-1}$.

At a constant tower draught, the emission volume will reduce by 15%, or $0.333 \text{ m}^3 \text{ s}^{-1}$. Thus, the airflow will reduce to $0.667 \text{ m}^3 \text{ s}^{-1}$, and the humidity ratio will increase to 1.13, which corresponds to an equilibrium temperature of 361.5K, and a velocity head pressure of 44.9 N m^{-2} . Similar calculations for a double row of arrestors occupying 30% of the area show that the humidity ratio will increase to 2.26, corresponding to an equilibrium temperature of 366K, and a velocity head pressure of 28.2 N m^{-2} . The line JKL on Fig. 75 thus shows the lower limiting conditions, assuming the arrestors are installed in the vertical plane. It is

found in practice that, due to the angle of the arrestors, the actual peak results lie to the right of the line JKL.

Consider next the upper limiting conditions for the peak emission, which can be constructed on the basis that there is no reduction in exit velocity on installation of arrestors. The reduction in velocity head pressure is then due entirely to changes in emission density, the line JM being constructed as follows:-

$$\begin{aligned} \text{e.g.} \quad u &= 13 \text{ m s}^{-1} \\ \text{At } 357\text{K}, \quad \rho &= 0.787 \text{ kg m}^{-3} \\ \text{thus } P(\text{V.H.}) &= 66.5 \text{ N m}^{-2} \end{aligned}$$

$$\begin{aligned} \text{At } 373\text{K}, \quad \rho &= 0.586 \text{ kg m}^{-3} \\ \text{thus } P(\text{V.H.}) &= 49.5 \text{ N m}^{-2} \end{aligned}$$

In practice, it is found that the actual peak values lie below the line JM. The results for configuration A at various inclinations are shown on Fig. 75. It can be seen that increase in pressure drop pushes the equilibrium further to the right. At exit temperatures above 373K, some steam will be emitted from the base of the tower.

Thus, with the installation of arrestors, there is a move to higher emission temperatures, which will lead to lower values of N due to less condensation, and should produce enhanced water vapour emissions. This is confirmed in the next section by calculations based on published work.

6.2 RATES OF STEAM EMISSION BASED ON PUBLISHED STUDIES

Studies have been published of quenches from 4m oven discharges which allow steam emission rates to be calculated. The earliest was by Jackson and Waple (19), where the tower consisted of three parallel-sided bays, each 23.2m^2 in area and 13.7m high. Emissions were reported separately for each bay, and the emissions of air and water vapour were calculable throughout the quench. Results for the centre bay only, open and with arrestment, are shown in Fig. 76.

In the open tower, at the peak temperatures, both air and water vapour emissions were at their maximum values. However, when arrestors were installed:-

- (a) the entrained air mass overall was reduced, and fell sharply with increase in temperature, after passing a peak around 330K.
- (b) the mass emission of water vapour continued to increase and followed an operating line which was lower than for the open tower, but reaching higher values at the more elevated temperatures. (To confirm that the water vapour emission overall was higher with arrestment, the calculated emissions from the three bays were combined. At peak conditions, the emission rate for water vapour rose from 36.1kg s^{-1} for the open tower to 66.3kg s^{-1} for the tower with arrestment).

These findings are in line with the conclusions of the theoretical studies in section 6.1.

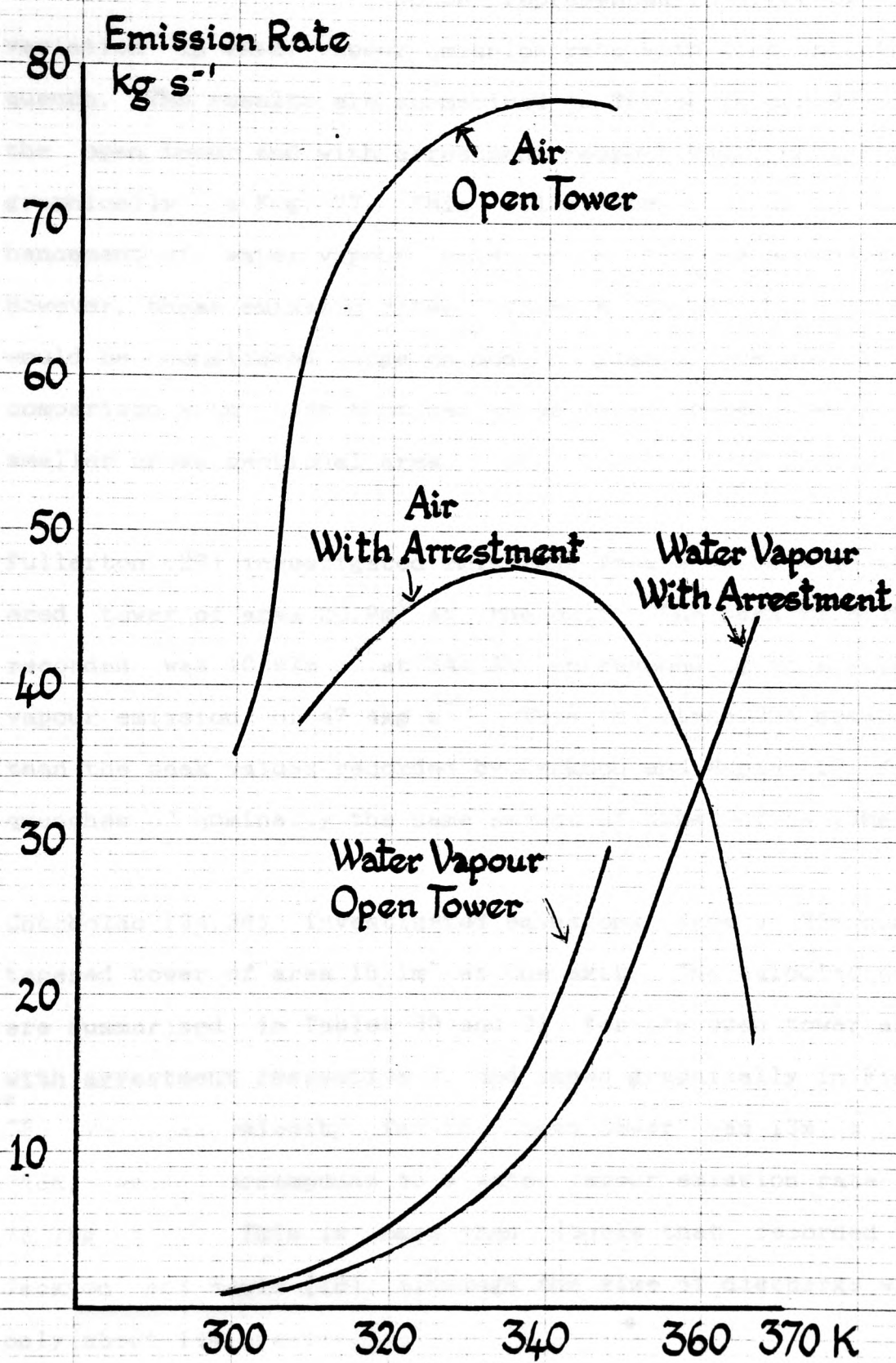


Fig. 76
Quench Tower Operating Lines
[Jackson and Waple Data]

The above results can also be represented in terms of the variation in water vapour emission rate with time into the quench. The results are summarised in Tables 28 and 29 for the open tower and with arrestment respectively, and shown graphically in Fig. 77. This illustrates clearly the enhancement of water vapour emission on fitting arrestors. However, these emission rates, from a tower whose area would be considered large on modern plants, are modest by comparison with those that can arise from tapered towers of smaller cross-sectional area.

Fullerton (26) investigated emissions from a 30.5m high tapered tower of area 20.9m^2 at the exit. The peak velocity recorded was 10.97m s^{-1} at 344.2K, corresponding to a water vapour emission of 47.4kg s^{-1} . This is circa 30% greater than the peak values recorded by Jackson and Waple (19) for quenches of nominally the same amount of coke (circa 13Mg).

Chocholac (34,36) investigated emissions from a 25m high tapered tower of area 18.1m^2 at the exit. The calculations are summarised in Tables 30 and 31 for the open tower and with arrestment respectively, and shown graphically in Fig. 78. The peak velocity for the open tower was 13m s^{-1} at 356K, which corresponds to a water vapour emission rate of 75.7kg s^{-1} . This is more than double that recorded by Jackson and Waple (19), although the size of discharge was only about 14% greater.

For the tower with arrestment, the arrangement of arrestors

Time s	Bay	u m s ⁻¹	Temp. K	H ₂ O Emission kg s ⁻¹
20	A	1.82	321)
	B	5.30	348	) 36.1
	C	2.12	320)
30	A	1.82	313)
	B	5.30	348	) 35.3
	C	2.12	321)
60	A	1.33	304)
	B	3.98	334	) 14.8
	C	1.33	311)
90	A	0.73	291)
	B	3.25	321	) 6.3
	C	0.73	299)
120	A	0.73	292)
	B	2.65	311	) 3.5
	C	0.73	300)
150	A	0.73	290)
	B	1.72	304	) 2.0
	C	0.73	300)
180	A	0.73	290)
	B	1.33	299	) 1.4
	C	0.73	299)

Table 28

WATER VAPOUR EMISSION RATES - OPEN TOWER
JACKSON AND WAPLE DATA (19)

Time s	Bay	u m s ⁻¹	Temp. K	H ₂ O Emission kg s ⁻¹
20	A	3.78	331)
	B	3.97	367	) 66.3
	C	3.18	338)
30	A	2.78	327)
	B	3.97	361	) 61.3
	C	3.45	348)
60	A	1.13	298)
	B	2.98	346	) 21.8
	C	1.99	333)
90	A	0.53	293)
	B	2.98	333	) 10.7
	C	1.33	313)
120	A	1.19	291)
	B	2.19	325	) 7.7
	C	1.79	318)
150	A	0.80	287)
	B	1.86	318	) 4.9
	C	1.72	311)
180	A	0.86	286)
	B	1.46	308	) 2.5
	C	1.33	303)

Table 29
WATER VAPOUR EMISSION RATES - WITH ARRESTMENT
JACKSON AND WAPLE DATA (19)

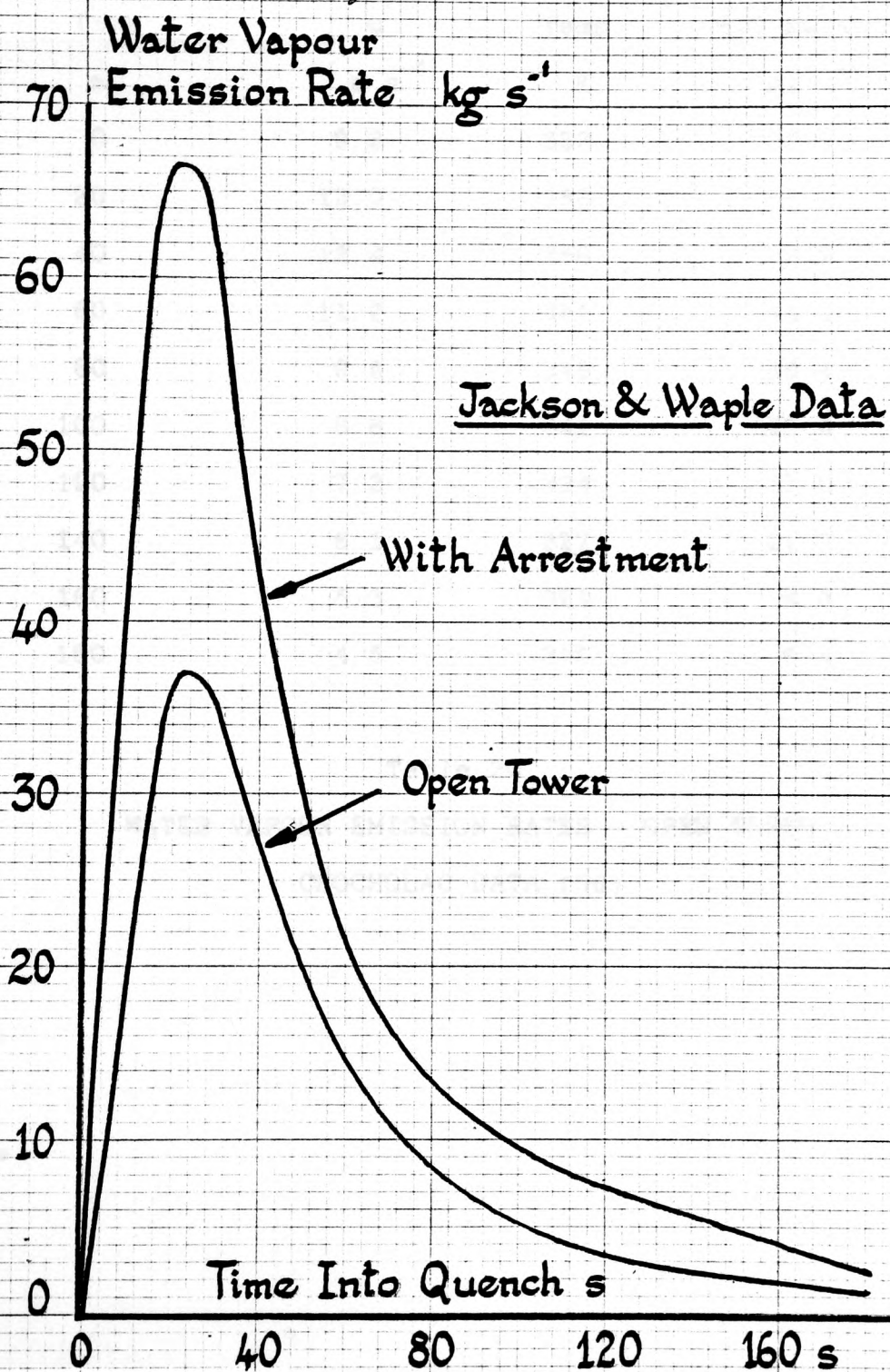


Fig 77

Water Vapour Emission Rate Versus
Period Into Quench

Time	u	Temp.	H ₂ O Emission
s	m s ⁻¹	K	kg s ⁻¹
0	9.8	333	22.1
20	13.0	356	75.7
40	12.4	356	72.2
60	11.2	351	54.4
80	9.5	345	36.4
100	8.6	341	27.4
120	7.2	334	17.0
140	6.1	327	11.2
160	5.3	321	8.3
180	4.5	315	6.4

Table 30
WATER VAPOUR EMISSION RATES - OPEN TOWER
CHOCHOLAC DATA (36)

Time	u	Temp.	H ₂ O Emission
s	m. s ⁻¹	K	kg s ⁻¹
0	9.6	348	41.9
20	11.5	370	109.3
40	10.9	368	101.7
60	10.2	363	77.3
80	8.9	359	58.2
100	6.8	353	35.5
120	5.5	347	23.1
140	5.0	339	14.2
160	4.6	335	11.1
180	4.2	329	8.2

Table 31

WATER VAPOUR EMISSION RATES - WITH ARRESTMENT

CHOCHOLAC DATA (36)

CONFIGURATION A - LOUVRE ANGLE 70°

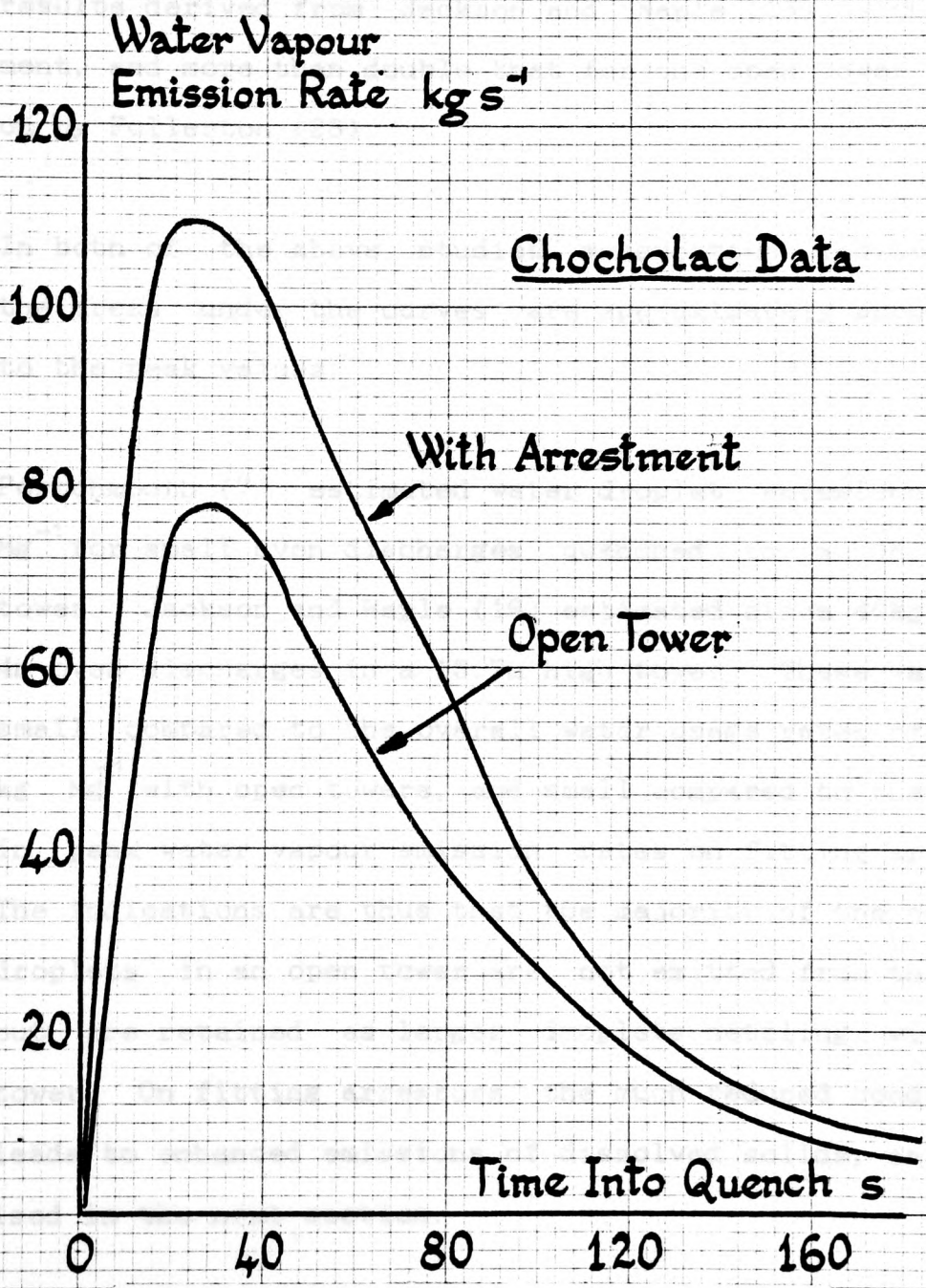


Fig. 78

WATER VAPOUR EMISSION RATE VERSUS
TIME INTO QUENCH

chosen for this example (configuration A inclined at 70°) was that with which the exit gases just reached a peak value of 373K. The peak water vapour emission rate rose to circa 110kg s^{-1} , which is circa two-thirds greater than the results derived from Jackson and Waple (19) with arrestment, and more than double that for the open tower reported on by Fullerton (26).

In both of the above studies, mensuration indicates that the areas under the curves are approximately proportional to the peak values.

Portchmouth (7) estimated water droplet emissions of 60kg Mg^{-1} for small oven discharges quenched in a 28.6m high tower. Jackson and Waple (19) estimated circa 40kg Mg^{-1} for 4m oven discharges in a 13.7m high tower. These values are small compared to the overall water usage rates of 450-500 kg Mg^{-1} with open towers, and small compared to the changes in peak water vapour emission rates on fitting arrestors. The indications are thus that the majority of the condensed droplets in an open tower are not emitted from the tower, but are retained as larger droplets settling within the tower. On fitting arrestors, the much reduced condensation leads to enhanced emissions of dissolved solids, as summarised in the next section.

6.3 THE EFFECT OF INSTALLING GRIT ARRESTORS ON EMISSIONS OF DISSOLVED SOLIDS

Enhancement of deposition of dissolved solids following installation of arrestors has been demonstrated in section 3.4 around a number of coke works in South Wales, using the Deposition CuSum technique.

Average annual values for both dissolved and undissolved solids in deposit gauges around B.S.C. Llanwern over the period 1977-1983 are shown in Table 32, together with the ratio between the two values. It can be seen that there have been two quite separate effects, in that the deposition of undissolved solids has decreased, while that of dissolved solids has increased. The increase in the ratio confirms the very significant effect of these changes.

	1977	1978	1979	1980	1981	1982	1983
<u>Llanwern 1</u>							
Dissolved	53.0	37.3	37.5	53.0	93.4	93.0	139.0
Undissolved	397	302	262	198	182	241	53
Ratio	0.13	0.12	0.14	0.27	0.51	0.39	2.62
<u>Llanwern 11</u>							
Dissolved	50.1	34.0	41.0	53.5	122	93	253
Undissolved	326	255	305	214	198	169	56
Ratio	0.15	0.13	0.14	0.25	0.62	0.55	4.52
<u>Hartridge</u>							
Dissolved	26.2	26.0	21.5	32.2	112	62.2	117.2
Undissolved	179	128	122	122	86	90	33.4
Ratio	0.15	0.20	0.18	0.26	1.30	0.69	3.51
<u>Nash</u>							
Dissolved	36.2	22.7	32.1	29.4	77.0	64.7	86.6
Undissolved	168	161	141	110	76	80	30.4
Ratio	0.22	0.14	0.23	0.27	1.01	0.81	2.85
<u>Bishton 1</u>							
Dissolved	50.2	32.4	33.0	47.4	125.6	79.6	140.5
Undissolved	344	272	224	179	173	139	60.5
Ratio	0.15	0.12	0.15	0.26	0.73	0.57	2.32
<u>Bishton 11</u>							
Dissolved	38.8	38.4	28.8	38.0	90.2	86.2	153.4
Undissolved	147	222	147	129	71	131	80
Ratio	0.26	0.17	0.20	0.29	1.27	0.66	1.92

Table 32
RATIO BETWEEN DISSOLVED AND UNDISSOLVED SOLIDS
IN DEPOSIT GAUGES AROUND BSC LLANWERN

6.4 THE QUENCH TOWERS AT B.S.C. LLANWERN

The areas of the upper outlets of the tapered quench towers at B.S.C. Llanwern have been reported (53) as 30.1m^2 for those serving the 4m ovens, and 50.7m^2 for the one serving the 6m ovens. Relatively speaking, these outlet areas are 50% and more greater than for the other tapered towers considered in this study, and consequently exit temperatures from open towers of the above dimensions would be lower than for the other towers studied.

No information is available on the temperatures of the steam plumes from open towers at B.S.C. Llanwern, but limited data have been obtained by observation on these towers as fitted with arrestment:-

- (a) At peak emission rates, there was considerable steam evolution from the base of the towers, indicating complete exclusion of entrained air.
- (b) The gases emitted from the top of the towers did not begin to condense until clear of the towers, and so it has been assumed that their temperature will be 373K at least.
- (c) Stop-watch checks of the time taken between the quench water hitting the incandescent coke and the steam emerging from the top of the tower indicate exit velocities of 5.0m s^{-1} for the towers serving the 4m ovens, and 4.4m s^{-1} for the tower serving the 6m ovens. (Both these values are +/- 10%).

Thus, for the towers serving 4m ovens:-

$$\text{Exit Velocity} = 5.0 \text{ m s}^{-1}$$

$$\text{Exit Area} = 30.1 \text{ m}^2$$

$$\text{Exit Flowrate} = 150.5 \text{ m}^3 \text{ s}^{-1}$$

$$\text{Density at 373K} = 0.586 \text{ kg m}^{-3}$$

$$\text{Water Vapour Emission Rate} = 88.2 \text{ kg s}^{-1} (+/- 10\%)$$

For the tower serving 6m ovens:-

$$\text{Exit Velocity} = 4.4 \text{ m s}^{-1}$$

$$\text{Exit Area} = 50.7 \text{ m}^2$$

$$\text{Exit Flowrate} = 223.1 \text{ m}^3 \text{ s}^{-1}$$

$$\text{Water Vapour Emission Rate} = 130.7 \text{ kg s}^{-1} (+/- 10\%)$$

The smaller towers at B.S.C. Llanwern deal with coke quenches of 13Mg. The corresponding peak emission rate for the tower studied by Chocholac, as shown in Table 31, is 109.3 kg s^{-1} , for a quench of 14.8Mg. Corrected to a quench of 13Mg, this gives a water vapour emission rate of 96.0 kg s^{-1} , which is within the range of the results found in the above observations. It should be noted that the Chocholac results chosen were those where the steam temperature just reached 373K, so there would have been no steam loss at the base of the tower.

An estimated value for the water vapour emission rate from an open tower of the B.S.C. Llanwern dimensions can be obtained from Fig. 79, which plots emission rates versus outlet areas from published studies. This shows the expected slow increase in rate from the large parallel-

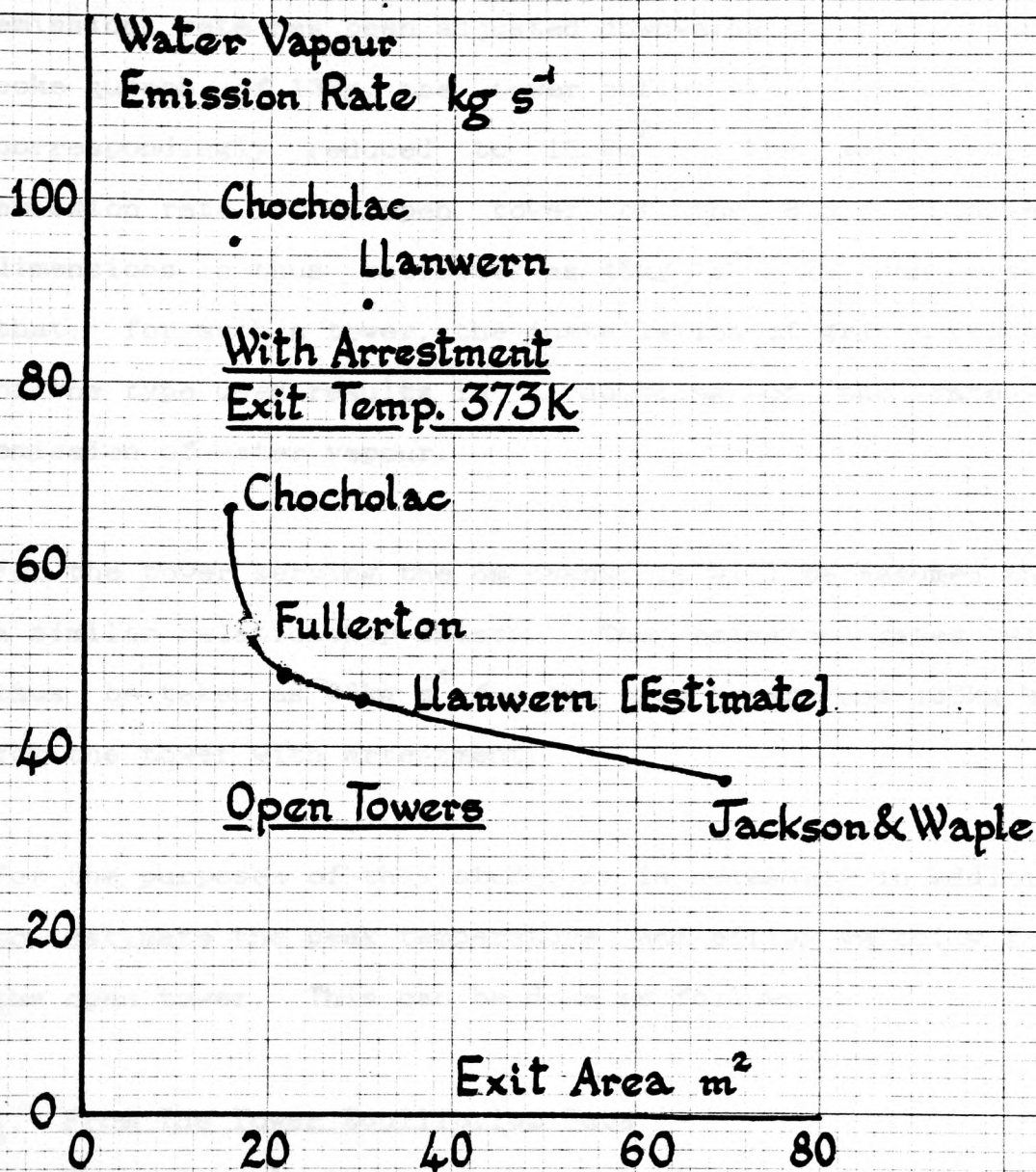


Fig. 79

Quench Tower Outlet Areas And
Water Vapour Emission Rates

sided tower studied by Jackson and Waple (19), with a rapid increase as the tower outlets are constrained in the tower studied by Chocholac (34). In the latter case, since the emission rate has been adjusted downwards to an equivalent coke quench of 13Mg, the tower outlet area has also been correspondingly reduced to 15.9m^2 . The water vapour emission rate for an open tower of the B.S.C. Llanwern dimensions is thus estimated as 45kg s^{-1} . It can be seen that, for such a tower, the installation of grit arrestors of the type used results in a doubling of the rate of emission of water vapour.

For the tower serving the 6m ovens, it will be assumed that a similar relationship exists. The emission rates will thus be taken as 66kg s^{-1} for the open tower, and 132kg s^{-1} for the tower with arrestment.

For the purposes of this study, it is necessary in addition to estimate the peak temperature and efflux velocity from the open tower. This can be done as follows:-

1. From The Tower Equilibrium Data

The exit velocity can be calculated using equation 6.1.3, assuming that Fig. 74 is of general application. As a cross-check, using the Fullerton (26) data, and taking the measurement point as 1.8m (6ft.) below the top of the tower, gives a calculated efflux velocity of 11.05m s^{-1} at 344K, compared to the reported value of 11.0m s^{-1} .

This method will predict a range of efflux velocities, depending on the gas temperature. Since the outlet area is considerably greater, relatively speaking, than the tower studied by Fullerton (26), the gas temperature will be less than 344K.

2. From The Humidity Ratios

Accepting that the water vapour emission rate is 66kg s^{-1} will enable the exit flowrate, and hence the efflux velocity, to be calculated for a range of temperatures.

The point at which the values calculated by these two methods coincide will give the probable exit conditions. From Fig. 80, it can be seen that these are, an efflux velocity of 7.93m s^{-1} , and an exit temperature of 338.3K. Thus, the efflux velocity will reduce by 45% on installation of arrestors, while the water vapour emission rate doubles.

The effect of the installation of arrestors on the maximum particle size elutriated can be estimated from Fig. 70. Ignoring the transit time correction, the efflux velocities quoted above indicate a theoretical maximum radius of circa $1950\mu\text{m}$ at 338K for the open tower, and circa $650\mu\text{m}$ at 373K with arrestment. Clearly, in the case of the towers at B.S.C. Llanwern, the major effect of installing this type of arrestment will be to abate the emissions of grit and dust. The effect of installing arrestors on plume rise will be considered separately in Chapter 7.

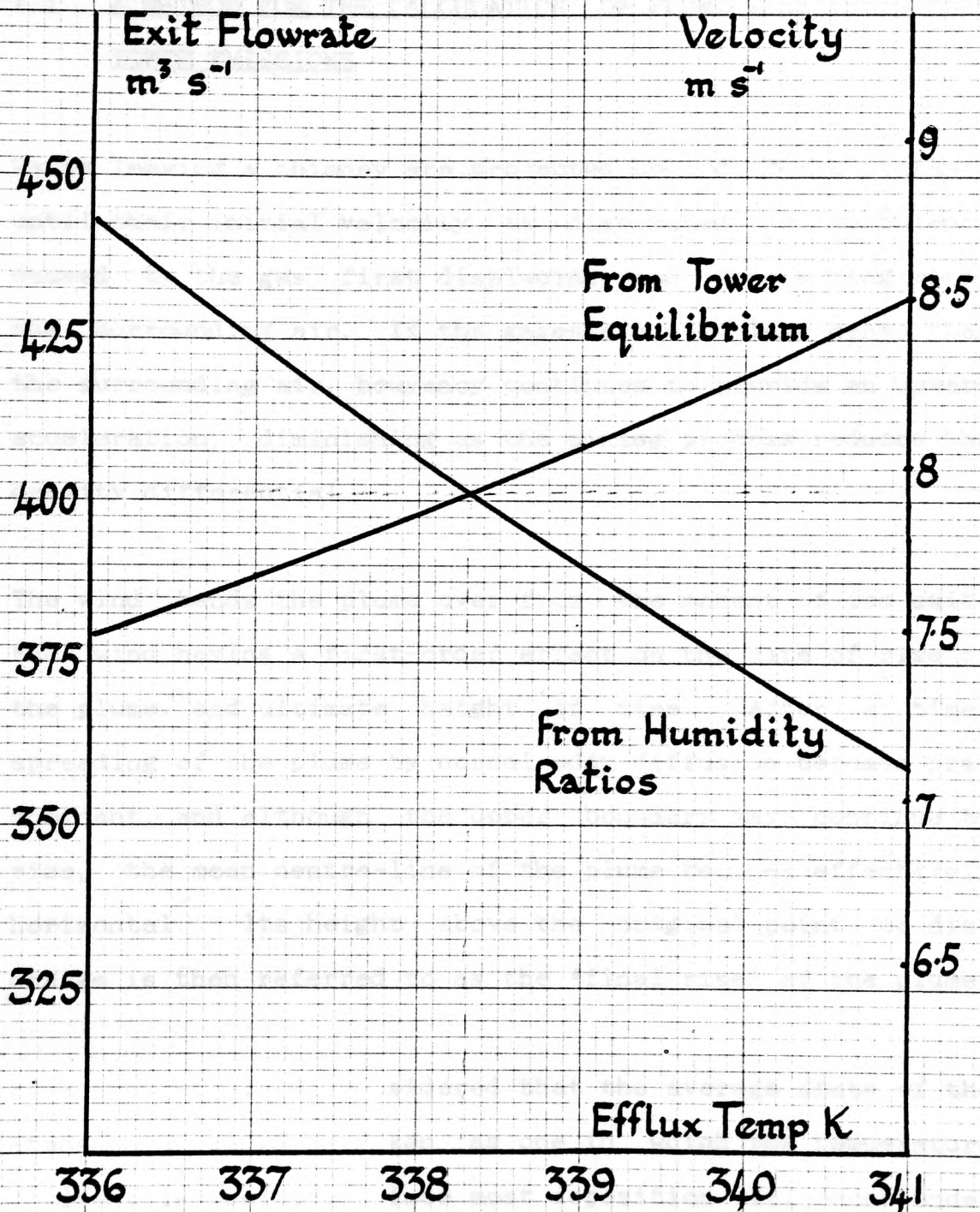


Fig. 80
 Estimation Of Peak Exit Conditions
 In Open Tower Serving 6m Ovens

CHAPTER 7

DISPERSION OF PARTICULATE MATTER FROM QUENCH TOWERS

7.1 A METHOD FOR THE CALCULATION OF PLUME RISE FOR QUENCH TOWER EMISSIONS

Gases leaving a chimney are projected upwards for a distance until their initial velocity is dissipated in turbulence caused by the gas first displacing, and then mixing with, the surrounding air. If the gases are also less dense than the surrounding air, bouyancy continues to provide an upward acceleration, diminishing as the mixing process reduces the density differential.

The wind bends the plume over from the moment of its exit, the wind having a first-order effect on the rate of rise of the plume, and ultimate height of rise. After a time, spreading of the plume by normal eddy diffusion becomes predominant, and although the upper boundary may continue to rise, the mean centre-line of the plume becomes effectively horizontal. Its height above the original point of discharge is then referred to as the 'final rise' of the plume.

Bosanquet et al (4) considered that the average state of the atmosphere could be taken as one in which the temperature gradient is positive, since most deposition will occur under such conditions. He used a potential temperature gradient of $3^{\circ}\text{C km}^{-1}$, which has also been used in this study. It is proposed that, for this study, the maximum height attained

by the plume from a quench tower under these conditions should be taken as the effective height of discharge:-

$$\begin{array}{lclcl} \text{Effective} & & \text{Quench} & & \\ \text{Chimney} & = & \text{Tower} & + & \text{Plume} & (7.1.1) \\ \text{Height} & & \text{Height} & & \text{Rise} \end{array}$$

Thus, plume rise must be assessed before dispersion calculations can be done. In the case of emissions containing grit and dust, the particulate matter will be carried upwards with the rising gases. For the finest dusts, those with no appreciable settling velocity, the above formula is satisfactory for determination of effective chimney height. Coarse dusts, however, will not be carried so high, and since the quench tower is being considered as a natural draught elutriator, premature deposition of coarser dusts would be expected quite close to the source.

A scenario is postulated in which the coarser particles successively drop out as the upward velocity decreases, such that the effective height of discharge for the remaining largest particles would increase sequentially, until the final plume rise is reached only with the finest particles. An attempt has been made to evaluate such a scenario in this study.

7.2 THE BOSANQUET EQUATION FOR BOUYANCY PLUME RISE

The Bosanquet equation (9) was obtained by theoretical consideration of the behaviour of a parcel of warm air rising by bouyancy in a given atmosphere while being diluted, and hence cooled, by diffusion into the surrounding air. Some empirical factors, derived from observations of small to medium-sized installations, were employed, and it remains one of the few semi-theoretical equations.

He showed that the plume rise for a bouyant emission is given by:-

$$h = A w \left[f_I(x_0) + f_{II}(x_0) - \frac{\text{Correction}}{\text{Factor}} \right] \quad (7.2.1)$$

$$\text{where } A = \frac{1}{2 \pi \Delta^2} \frac{g G \theta}{T_w^4} \quad (7.2.2)$$

The terms have the following meanings:-

g = Gravitational acceleration (9.81 m s^{-2})

T = Temperature (K) at which density of flue gases is equal to that of ambient air.

u = Actual gas efflux velocity (m s^{-1})

w = Wind velocity (m s^{-1})

θ = Emission Temperature - T

Δ = Mean dilution coefficient (assumed 0.13)

G = Potential Temperature Gradient, the excess of the adiabatic over the actual lapse rate (taken as 3°C km^{-1})

$$\text{If } u/w > 0.48, \text{ Correction Factor} = \frac{0.615 x_o^{0.5}}{\left(\frac{u^2}{w} + 0.57\right)^{0.5}}$$

$$\text{If } u/w < 0.48, \text{ Correction Factor} = \left[1.311 - 0.90 \frac{u}{w}^{0.5} x_o^{0.5} \right]$$

$f_I(x_1)$ and $f_{II}(x_o)$ are evaluated from tables provided by Bosanquet (9). The first table relates x and $f_I(x_1)$, where $x = (t + t_o)/A$; t_o being the time required for the effluent gas to reach its exit velocity under the influence of bouyancy alone, and t the time elapsed since the waste gas left the chimney.

When x is very small,

$$f_I(x_1) = 1.054 x^{0.75} \quad (7.2.3)$$

When x is very large,

$$f_I(x_1) = \ln(x) - 0.12 \quad (7.2.4)$$

The second table relates x_o and $f_{II}(x_o)$, where $x_o = t_o/A$. If x_o is zero, the equation corresponds to a point source of heat, the upward velocity being due entirely to natural convection.

When x is very small,

$$f_{II}(x_o) = 0.527 x^{0.75} \quad (7.2.5)$$

When x is very large,

$$f_{II}(x_0) = 1.311 x^{0.75} - 0.5 \ln(x_0) - 1 \quad (7.2.6)$$

The relationship between T and θ for the case of mixtures of air and water vapour is shown in Figure 81, see section 7.3.

HMI-API has used the Bosanquet equation almost exclusively in determination of the "first assessment" of chimney height for new installations. It has proved to be suitable for heat emission sources up to the power station category, and remains in use for bouyancy plume rise up to 220m.

In view of the large number of calculations required in the present study, the Bosanquet equation and the accompanying tables have been converted into a computer programme, which appears as Appendix 2.

7.3 THE EFFECT OF EMISSION TEMPERATURE ON GAS BOUYANCY IN A QUENCH TOWER

The following example illustrates the use of the Bosanquet equation (9) for calculating gas bouyancy :-

Assume efflux temperature	= 373K
Density of air at 288K	= 1.22 kg m ⁻³
Assume density of gas at 288K	= 1.10 kg m ⁻³

$$\begin{aligned}\text{Then } T &= \frac{1.10 \times 288}{1.22} = 260\text{K} \\ \text{and } &= 373 - 260 = 113^{\circ}\text{C}\end{aligned}$$

Thus the gas, if it were at 260K, would have the same density as air at 288K. With the usual type of problem encountered in plume rise calculations, there is little change in gas composition with changes in emission temperature. However, for quench towers emissions, the gas composition is considered to change as proposed by Wagener (16).

Fig. 67 shows the effect of such changes on the density of the gas in a quench tower, and compares it with that of air over the range 273-373K. As the temperature approaches 373K, the emissions become increasingly more bouyant. These densities have been used to calculate T and θ over the range 273-373K. The results are shown in Fig. 81, which indicates for example that whereas at 373K the actual difference is 85°C, θ in fact equals 193°C.

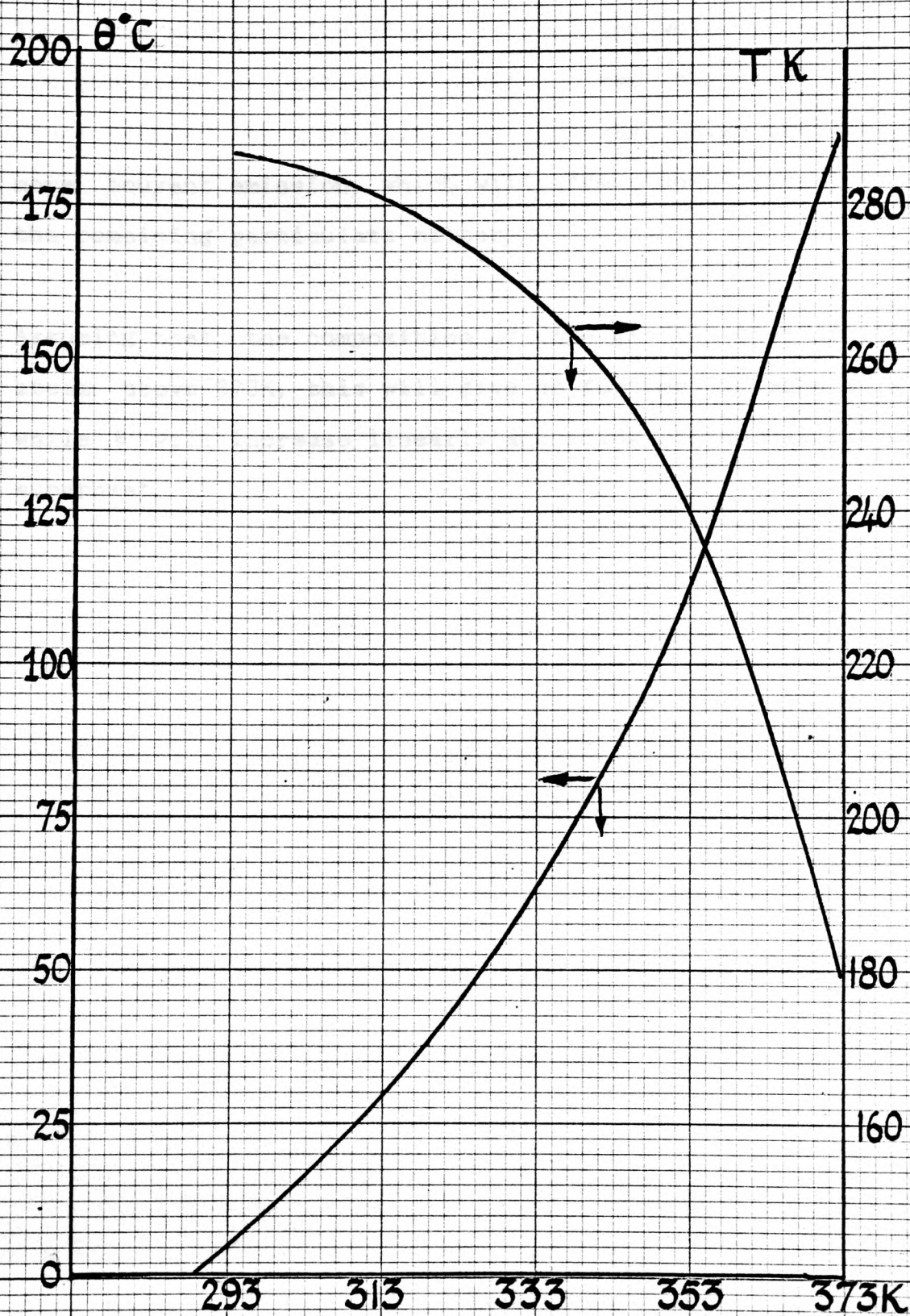


Fig.81

Thermal Bouyancy Of
Air/Water Vapour Mixtures

Thus, the modification of gas composition which reduces the maximum size of particle elutriated from the tower due to the increased terminal settling velocity, also produces a more bouyant emission, which will affect the dispersion of the remaining particulate matter.

Assuming that the composition of the gas is that of 100% steam above 373K, this will give no further increase in T, while θ will increase linearly according to the amount of superheat.

7.4 THE CALCULATION OF t

The value of t_0 depends on the ratio of the momentum Qu to the bouyancy $gQ\theta/T$, and is given by:-

$$t = 4uT/3g\theta \quad (7.4.1)$$

t has been evaluated for some published quench tower studies, and the results are given in Table 33 for quench towers serving 4m ovens.

STUDY	$u \text{ (m s}^{-1}\text{)}$	$t \text{ (s)}$
Tapered Open Tower (26)	10.97	4.23
Parallel-sided Open Tower (19)	5.30	1.75
Parallel-sided With Arrestment (19)	3.97	0.65

Table 33.

TIME TAKEN TO REACH EFFLUX VELOCITY

The effect of installing arrestors on the bouyancy of the effluent gas is very clear from these calculations. It should be noted that the results from Jackson and Waple (19) are based on the centre bay only.

7.5 TIME TO REACH FINAL PLUME RISE

Bosanquet (9) showed that the upper integration limit of $(t+t_0)$ is given by:-

$$t = 1.527 (2T/gG)^{0.5} \quad (7.5.1)$$

He considered that, as a conservative estimate under average conditions, one could take t_1 as 200s. In order to obtain the effective chimney height governing the concentration at any distance downwind, he indicates that t_1 should be taken either as the actual value of $(t+t_0)$ or 200s, whichever is the smaller.

Table 34 shows the calculated values for t_1 based on some published data for quench towers serving 4m ovens. In the case of the data from Jackson and Waple (19), t_1 is now based on the combined emission from the three bays. Since equation 7.5.1 contains no term relating to the quantity of emission, Fig 82 should have general application.

STUDY	t_1 (s)
Tapered Open Tower (26)	206.6
Parallel-sided Open Tower (19)	208.5
Parallel-sided With Arrestment (19)	201.3
Towers With Emissions At 373K	173.4

Table 34

EXAMPLES OF TIMES TO REACH FINAL PLUME RISE

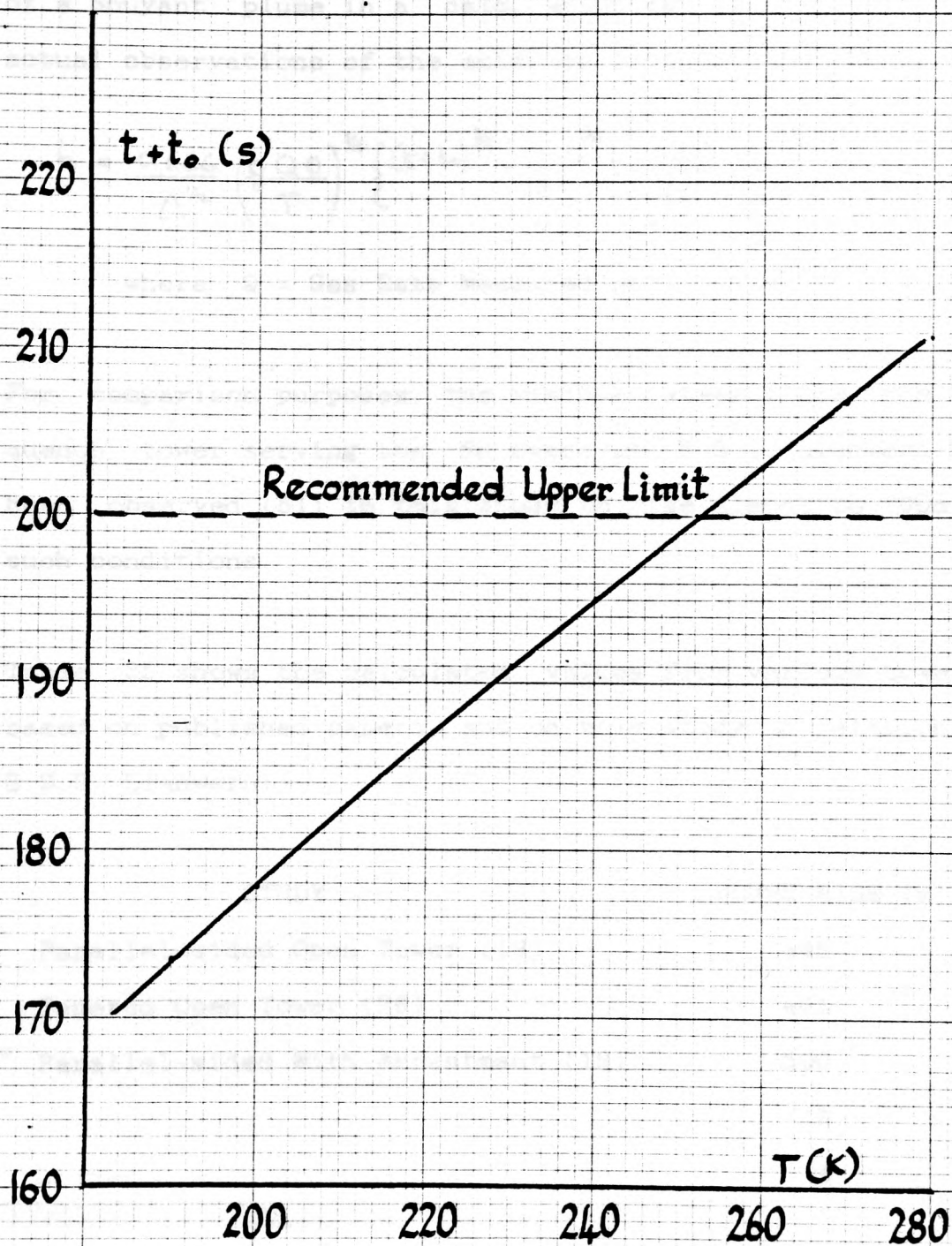


Fig.82
Time To Reach Final Plume Rise Versus
Equivalent Ambient Temperature

7.6 THE RISE OF A BOUYANT PLUME UNDER CALM CONDITIONS

Bosanquet (9) provided the following equation for the rise of a bouyant plume in a calm, which can be compared with actual observations of the emission from a quench tower.

$$h = \frac{0.666}{\Delta^{1/2}} \left(\frac{g Q \theta}{T} \right)^{1/4} \left\{ (t+t_0)^{3/4} - \frac{1}{2} t_0^{3/4} \right\} - \frac{0.283}{\Delta} \left(\frac{Q}{u} \right)^{1/2} \quad (7.6.1)$$

where Q = Gas Rate Measured at T ($m \ s^{-1}$)

For comparison purposes, the visible steam plume from the quench tower serving the 6m ovens at B.S.C. Llanwern has been observed (51) in this study to rise almost to 600m in such conditions.

Table 35 shows the calculated values from various towers, based on published papers, and on this study in relation to B.S.C. Llanwern:-

STUDY	PLUME RISE (m)
Parallel-sided Open Tower (19)	445
Tapered Open Tower (26)	461
Parallel-sided With Arrestment (19)	500
Llanwern Open Tower (6m Ovens)	515
Llanwern With Arrestment (6m Ovens)	554

Table 35

PLUME RISE FROM QUENCH TOWER IN CALM CONDITIONS

7.7 THE EFFECT OF WIND VELOCITY ON BOUYANCY PLUME RISE

Bosanquet (4) indicated that the equations for the rise of a bouyant plume were applicable for any value of wind velocity. He considered however, that it was sufficiently accurate to take a mean value for wind velocity, and 4.57m s^{-1} (15ft s^{-1}) was suggested arbitrarily as a working mean for calculating dust deposition. Although meteorological data were incomplete, the true value was known to lie between $3.05\text{--}6.1\text{m s}^{-1}$ ($10\text{--}20\text{ft s}^{-1}$). Typical worked examples within that range had shown that wind variations affected the amount of dust deposit only slightly. Decreasing wind speed increases the rise of the plume, which becomes less dilute. In installations such as large boilers, these effects were considered approximately to cancel one another.

Equation 7.2.1 can be used to evaluate the effect of wind velocity on plume rise. As an illustration of this effect, the data for the open tapered tower studied by Fullerton (26) have been taken, at the peak emission rate:-

Gas Efflux Velocity	= 10.97m s^{-1}
Actual Gas Volume	= $229.11\text{m}^3\text{s}^{-1}$
Actual Gas Temperature	= 344.2K
Actual Gas Density	= 0.902kg m^{-3}

From which:	T	= 255K
	θ	= 89°C
	Q at T	= $169.78\text{m}^3\text{s}^{-1}$

The effect on plume rise of wind velocity from $1 - 20 \text{ m s}^{-1}$ has been evaluated, and the results are shown in Table 36 and Fig. 83. In section 7.6 the plume rise in a calm was shown to be 461.4m, and it can be seen from Fig. 83 that increase in wind speed then has a very important effect. At the upper end of the range, ignoring any effect of downwash, the plume rise is insignificant. Under extremely high winds, the plume from a quench tower serving 4m ovens has been observed during this study to come to ground within 200m of the tower.

Clearly, the value chosen for wind speed will have an important bearing on this study. To illustrate the importance, actual plume paths have been evaluated for the above case, at varying wind velocity. The velocities chosen for this illustration were 4, 5, and 6 m s^{-1} , and the results are shown in Table 37 and Fig. 84. It can be seen that the upward velocity of the plume will be very dependent on the wind velocity. It is the upward velocity of the plume which governs the effective height in the plume path at which particles of a given size will begin their descent.

Data have been published (43) on the distribution of Pasquill weather stability categories and mean wind speeds around the U.K., and these show that for the B.S.C Llanwern site, the mean wind speed can be taken as 5 m s^{-1} . This value will therefore be used in the remainder of this study for the dispersion calculations.

Wind Velocity	Total Plume Rise
m s ⁻¹	m
Calm	461.4
1	434.0
2	359.9
4	183.4
5	127.5
6	92.1
8	53.0
10	33.7
12	23.3
14	17.2
16	13.2
18	10.6

Table 36
EFFECT OF WIND VELOCITY ON TOTAL PLUME RISE
FULLERTON DATA

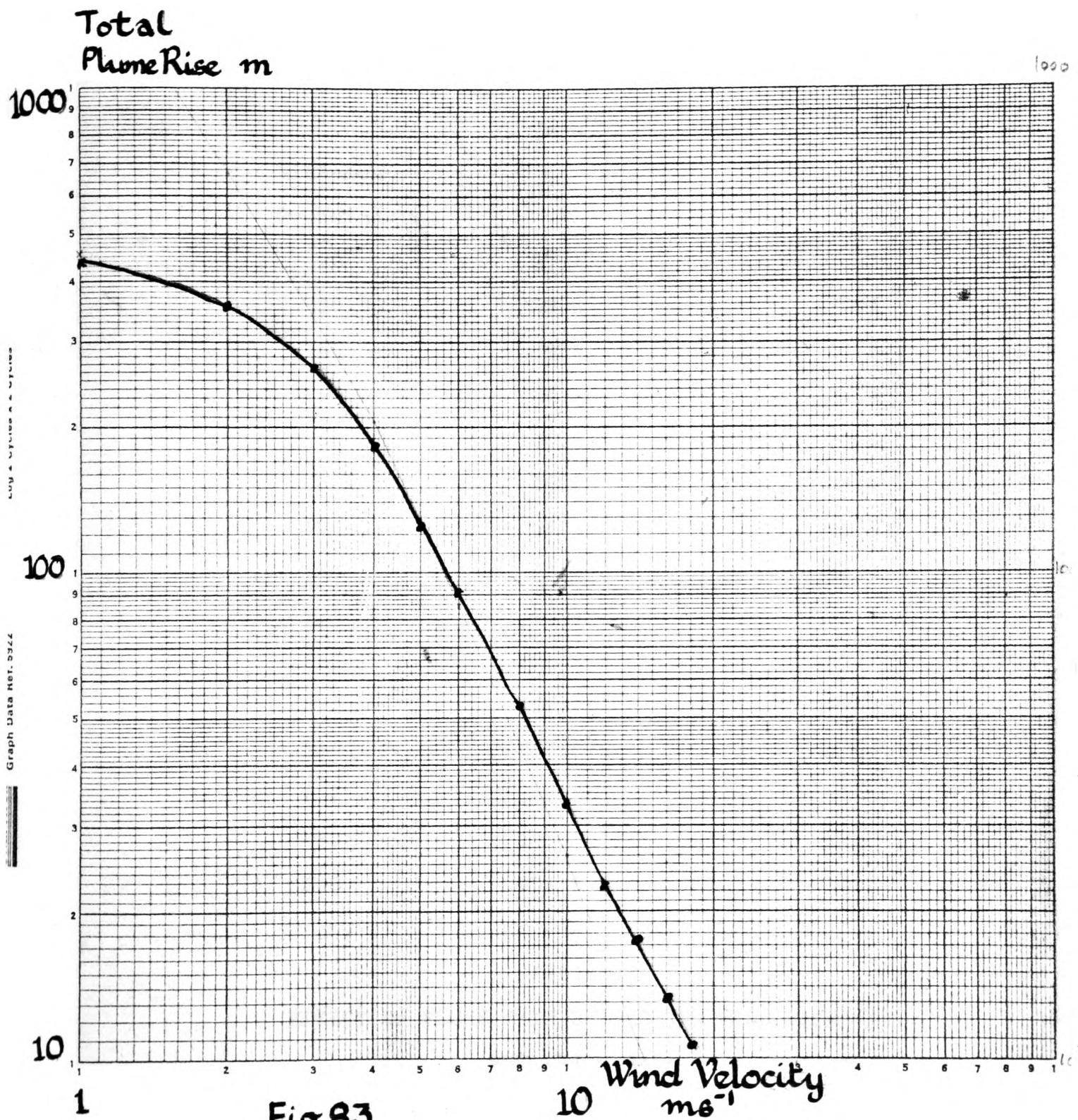


Fig 83
Effect Of Wind Velocity On Total Plume Rise

Distance Downwind (m)	Wind Velocity		
	4m s ⁻¹	5m s ⁻¹	6m s ⁻¹
20	27.1	24.8	23.1
30	33.6	29.2	26.1
40	39.5	33.1	28.8
50	44.8	36.6	31.2
60	49.8	40.1	33.5
80	58.8	45.9	37.2
100	66.8	51.0	40.6
150	83.8	61.6	47.4
200	97.9	70.1	52.8
250	109.8	77.1	57.2
300	120.2	83.3	61.1
350	129.2	88.6	64.5
400	137.6	93.4	67.2
450	145.0	97.7	69.8
500	151.8	101.6	72.0

Table 37
EFFECT ON PLUME PATH OF VARYING WIND VELOCITY
FULLERTON DATA

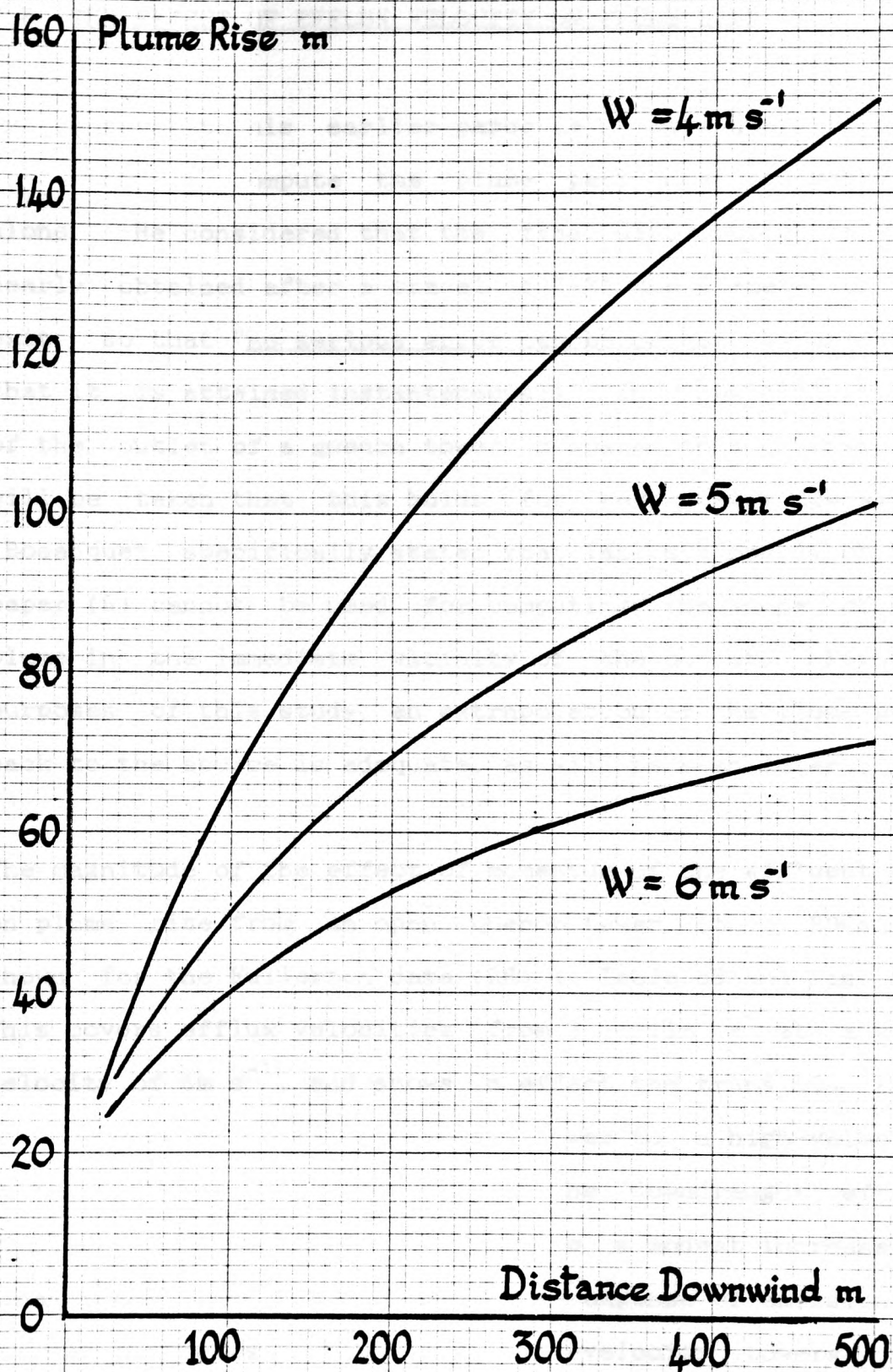


Fig. 84

Paths Of Bouyant Plumes At Various Wind Velocities
Fullerton Data - Open Tower

7.8 THE EFFECT OF EFFLUX VELOCITY ON PLUME RISE

By contrast to his earlier paper (4), Bosanquet (9) does not attempt to compute the plume path due to momentum alone. He considered that the final distribution is very nearly obtained after a travel of 2-3X the diameter of the exit, so that "no serious error can be caused" by assuming that it is attained instantaneously. In view of the size of the outlet of a quench tower compared to a chimney, it will be taken that this holds for, say 40-50m downwind. (Bosanquet specifically states that Tables I and II of his paper (9) cannot be used for computing the shape of the plume in the immediate vicinity of the outlet. For the purposes of this study, an extrapolation of the plume path back to the source is adequate, as will be seen later.)

The magnitude of the effect of momentum of the effluent gas on plume rise from an open quench tower ($t_1 = 200s$) is shown for the Fullerton data (26) in Table 38 and Fig. 85. This covers efflux velocities from 3 - 11m s⁻¹ at a wind velocity of 5m s⁻¹, and shows in effect the transition from a low-velocity (parallel-sided) tower to a high-velocity (tapered) tower. The reduction in the "downdraught" effect at higher efflux velocities leads to a modest increase in final plume rise, but that is at the expense of emission of coarser particles. With the high-velocity towers, the tower height would need to be greater to maintain the same equilibrium temperatures, so that the effective height of discharge could be significantly increased.

Efflux Vel.	$Awf_I(x_1)$	$Awf_{II}(x_0)$	Correction	Final Plume Rise
$m\ s^{-1}$	m	m	m	m
11	135.4	+0.4	-8.1	127.7
10	135.4	-0.1	-8.4	126.9
9	135.4	-0.5	-8.7	126.2
8	135.4	-0.9	-9.1	125.4
7	135.4	-1.3	-9.4	124.7
6	135.4	-1.6	-9.8	124.0
5	135.4	-1.8	-10.1	123.5
4.5	135.4	-1.9	-10.2	123.2
4	135.4	-2.0	-10.3	123.0
3.5	135.4	-2.0	-10.3	123.0
3	135.4	-2.0	-10.2	123.2
2	135.4	-1.9	-9.7	123.8

Table 38

EFFECT ON PLUME RISE OF VARYING EFFLUX VELOCITY
FULLERTON DATA

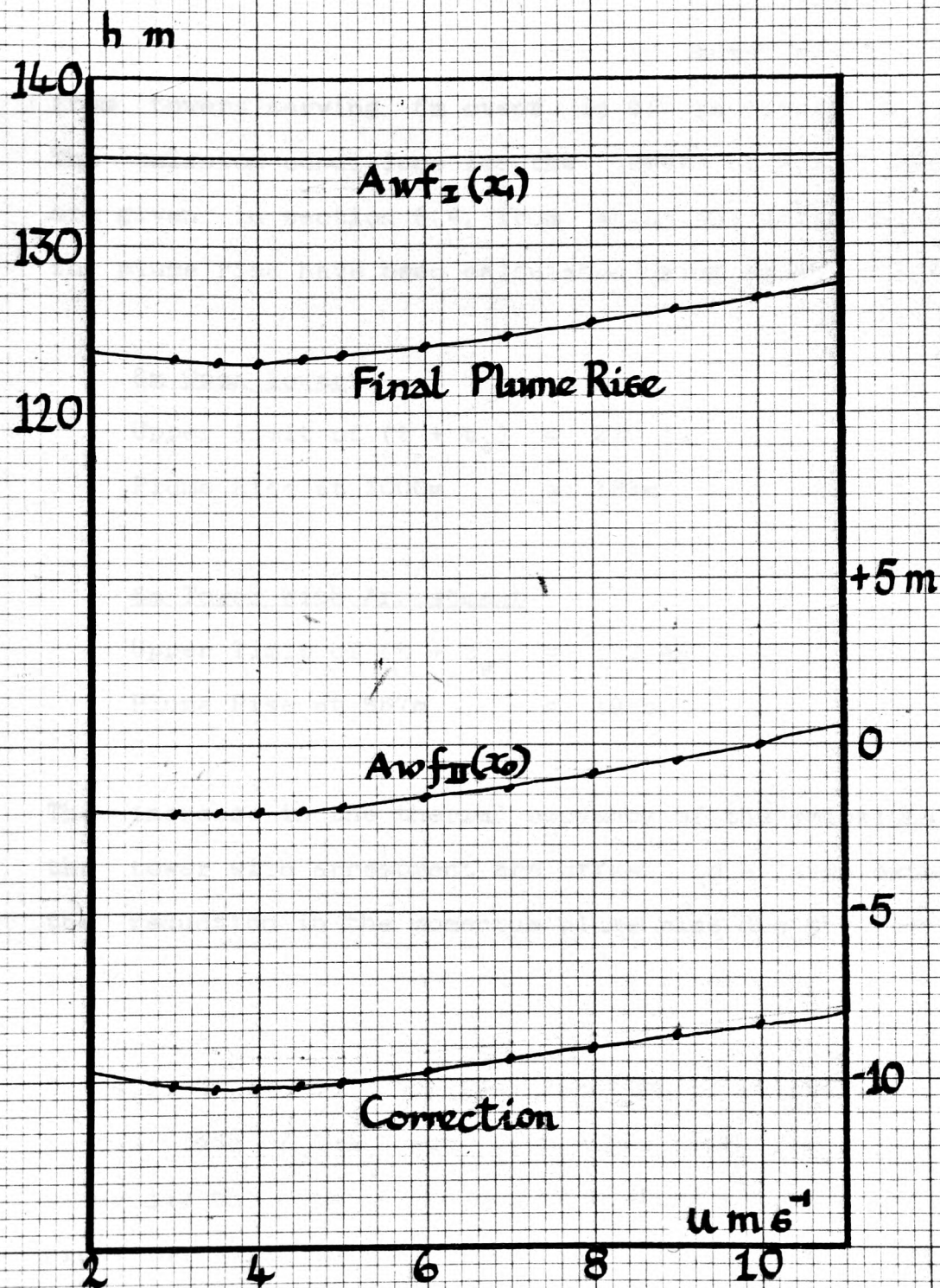


Fig. 85
The Effect On Plume Rise
Of Varying Efflux Velocity
[Fullerton Data]

7.9 THE PLUME RISE FROM TOWERS SERVING 6m OVENS

Most published data on quenching refers to towers serving 4m ovens. However, for the present study, the dispersion from towers serving 6m ovens is of particular interest. The emission conditions for the towers at B.S.C. Llanwern are given in section 6.4, from which the following values for plume rise have been calculated using equation 7.2.1:-

6m Open Tower

Upper limit of $(t + t_0)$ = 210.1s

Plume Rise at 1000m = 165m

6m Tower With Arrestment

Upper limit of $(t + t_0)$ = 173.4s

Plume Rise at 867m = 191m

The increase in the thermal bouyancy of the emissions from the tower with arrestment are offset to a large extent by the reduction in the momentum plume rise due the reduction in the peak emission rate on fitting arrestors.

The effect of the water gas reaction is relatively minor. In the case of the tower with arrestment, for theoretical water gas the density reduces to 0.490kg m^{-3} , and the plume rise increases to 203m, constrained by a maximum value for $(t + t_0) = 158.6\text{s}$. In view of the uncertainties involved, this modest increase in plume rise can be ignored.

7.10 THE VERTICAL VELOCITY OF A BOUYANT PLUME

The data for the quench towers serving the 6m ovens at B.S.C. Llanwern will be used to illustrate the method used to calculate the vertical velocity of a bouyant plume. The plume path is calculated using equation 7.2.1 at a wind velocity of 5m s^{-1} , using intervals of 10, 20 and 50m as appropriate. Each incremental increase in plume rise is divided by the time taken for the plume to travel the appropriate distance downwind, to give the mean vertical velocity during that interval. Fig. 86 shows the results.

For the open tower, the vertical velocity falls rapidly to below 3m s^{-1} by the time the plume has travelled one tower diameter downwind, a massive deceleration from the efflux velocity of 7.9m s^{-1} , due to turbulent mixing of the exit gas stream with the surrounding air. Since particles will fall from the plume when their terminal settling velocity exceeds the vertical velocity of the plume, it can thus be concluded that with high-velocity open towers there will be significant deposition of the coarsest particles in the immediate vicinity of the tower.

For the tower with arrestment, the vertical velocity, after dissipation of the momentum plume rise, remains higher than for emissions from the open tower, for all distances downwind. However, the coarsest particles will not now have been emitted, and there will be improved dispersion of the remaining finer fraction on fitting arrestors.

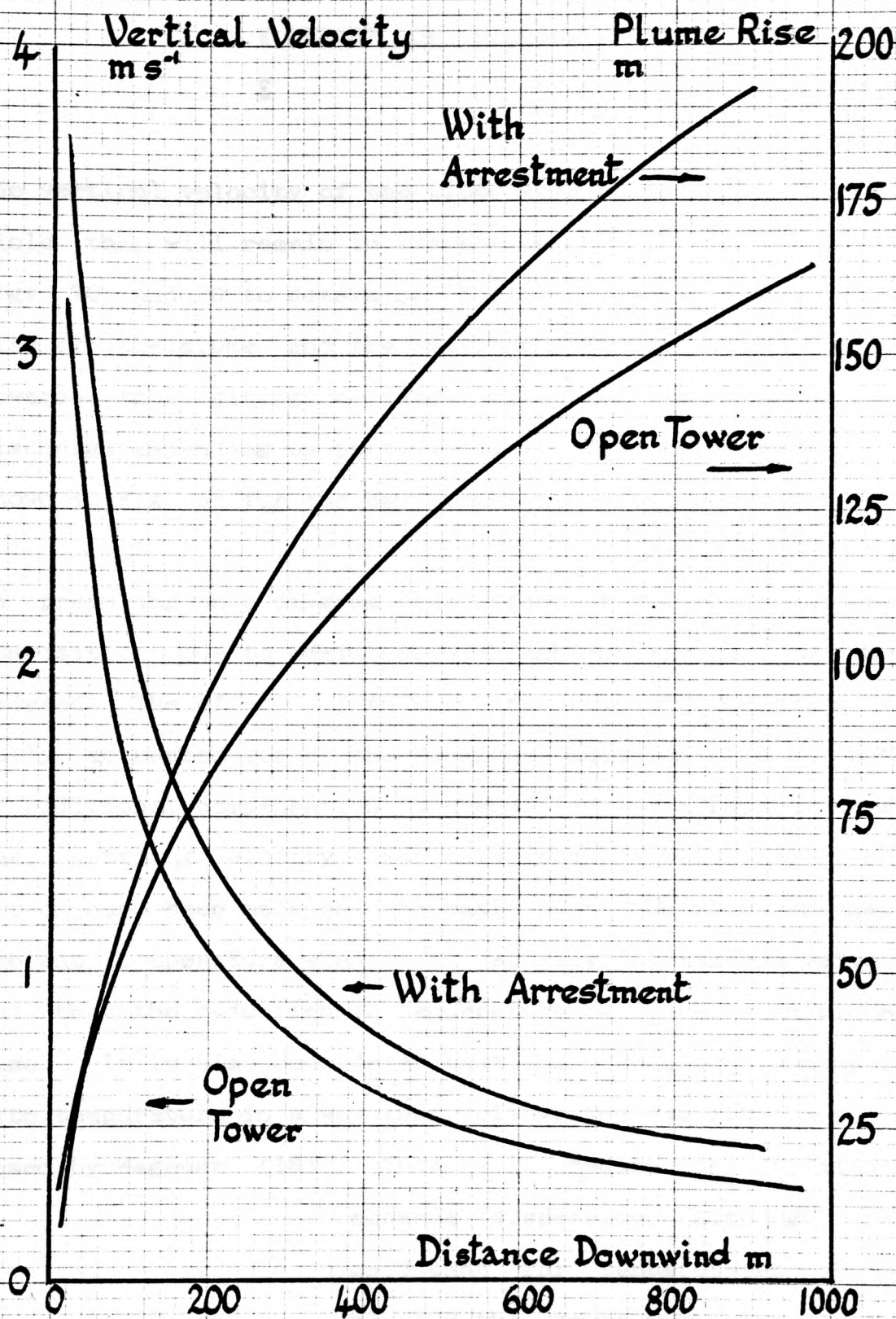


Fig. 86

Vertical Velocity Of A Bouyant Plume

7.11 THE EFFECTIVE HEIGHT OF DISCHARGE IN RELATION TO PARTICLE SIZE

The vertical velocity of the plume governs the size of particle that will remain in suspension. It is possible from Figs. 70 and 86 to determine the relationship between the rise of the plume and the maximum particle size carried upwards, thus giving a range of effective heights of discharge depending on particle size. This relationship is shown in Fig. 87 for the open tower and with arrestment.

In preparing this diagram, the effect of the change in gas composition due to admixture with ambient air must be considered. The effect of this on the rise of the plume is fully accounted for by the Bosanquet equation (7.2.1), but an additional compensation is needed for the effect on terminal settling velocity. For this study, a tentative correction has been made on the basis that the plume reaches ambient temperature when $(t+t_0)$ attains its maximum value, and that the reduction in temperature is linear with plume rise. It is also considered that the composition changes with temperature in a way that follows the equilibrium proposed by Wagener (16). This will reduce the terminal settling velocity, and enhance dispersion, although the effect only becomes significant for temperatures above circa 340K, that is, only for the tower with arrestment. The corrections applied are shown in Table 39.

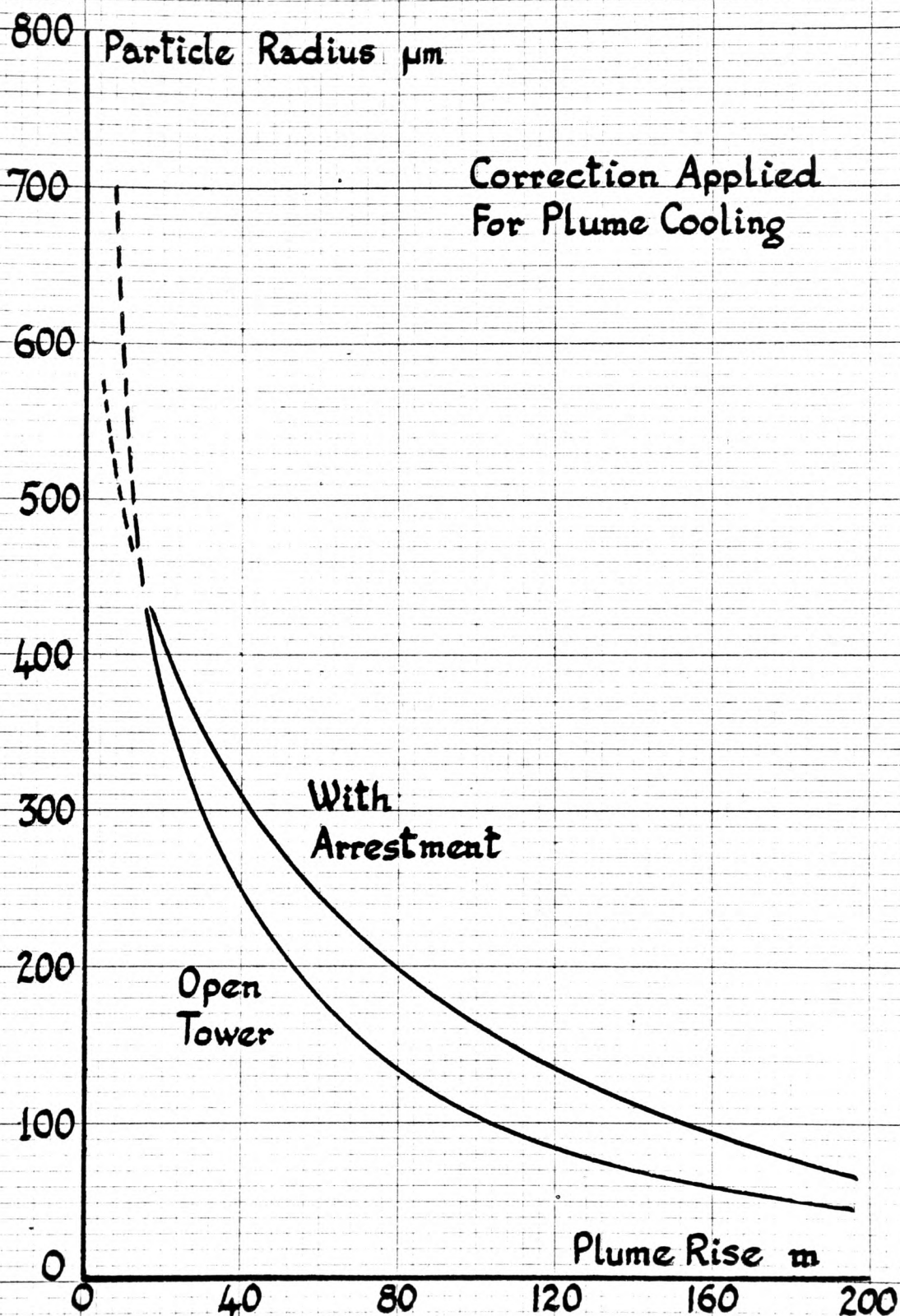


Fig. 87
Variation Of Maximum Particle Size In Suspension
With Plume Rise From Tapered Tower (6m Ovens)

	Open Tower	With Arrestment
Mean Efflux Temp. (K)	338	373
Excess Above Ambient ($^{\circ}\text{C}$)	50	85
Plume Rise (m)	165	191
Cooling Rate ($^{\circ}\text{C m}^{-1}$)	0.30	0.45

Table 39

TENTATIVE COOLING RATE WITH HEIGHT OF PLUME

Using figures 86 and 87, and based on a quench tower height of 25m, a diagram can be constructed which shows the effective height of discharge in relation to particle size and distance downwind. This is shown in Fig. 88. It can be seen that particles of a given size will be carried further upwards, and further downwind in the plume from the tower with arrestment than in that from the open tower. The dotted ISOTHERMAL lines join the corresponding positions in the two plume paths.

These effective heights of discharge can then be used to consider rates of deposition of particulate matter, using the method proposed by Bosanquet (4).

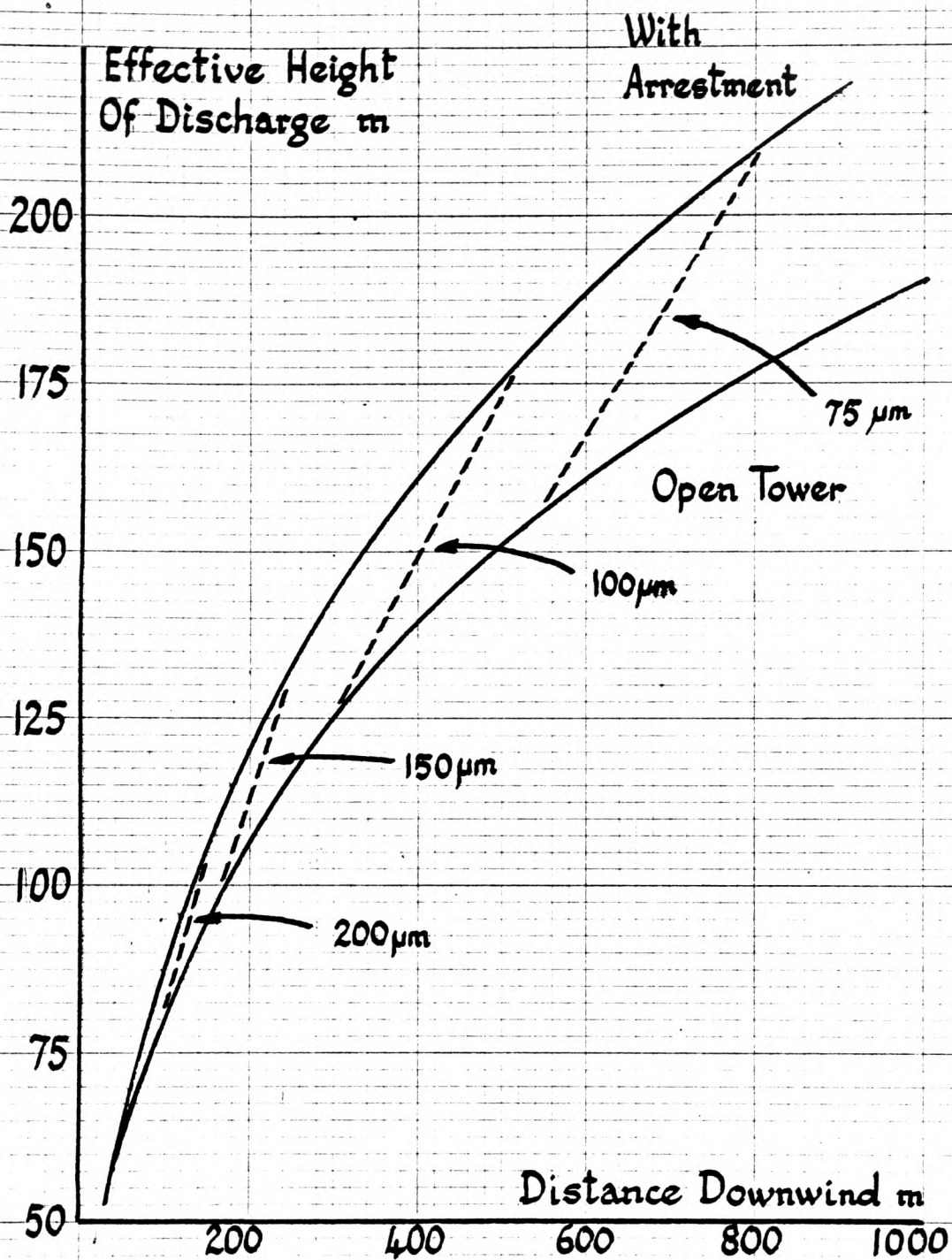


Fig. 88

Effective Height Of Discharge
As Function Of Distance Downwind
6m Ovens

7.12 THE DEPOSITION OF PARTICULATE MATTER FROM QUENCH TOWER EMISSIONS

In a streamlined wind, particles will follow a path of fall whose inclination to the horizontal is $\tan^{-1}(V_t/w)$, where V_t is the terminal settling velocity, and w is the wind velocity. The horizontal distance to the point of deposition is then given by:-

$$x = H_{\text{Eff}} \cdot w/V_t \quad (7.12.1)$$

With particles of size such that they have no finite settling velocity, equation 7.12.1 indicates that x would be infinite. However, Bosanquet (4) observed that in the turbulent atmosphere, the point of maximum ground level concentration occurred at $10.H_{\text{Eff}}$ from the source, and thus reasoned that the angle of fall should be $\tan^{-1}(0.1+V_t/w)$, which gives $x = 10.H_{\text{Eff}}$ in the limiting case as V_t tends to zero.

This construction has been used in the present study, with values of V_t calculated using the McDonald method (15). The distances to the point of maximum ground level concentration for various particle sizes are shown in Table.40 and Fig. 89 for a particle density of 1000kg m^{-3} . This indicates that the maximum deposition rates for the coarsest material ($>650\mu\text{m}$), emitted from the open tower, will be found within $2.H_{\text{Eff}}$ of the point of release. Since particles of this size will begin to fall from the

v/w	$\tan^{-1} (0.1+v/w)$	v m s^{-1}	Radius μm
0.9	1.00	4.5	594
0.8	1.11	4.0	518
0.7	1.25	3.5	444
0.6	1.43	3.0	384
0.5	1.67	2.5	328
0.4	2.00	2.0	260
0.35	2.22	1.75	225
0.3	2.50	1.50	192
0.25	2.86	1.25	166
0.2	3.33	1.00	140
0.15	4.00	0.75	100
0.10	5.00	0.50	80
0.075	5.71	0.375	66
0.05	6.67	0.25	50
0.03	7.69	0.15	40

Table 40

PARTICLE SIZES RELATIVE TO GIVEN ANGLE OF FALL.

AMBIENT AIR - PARTICLE DENSITY 1000kg m^{-3}

BOSANQUET et al, McDONALD (4,15)

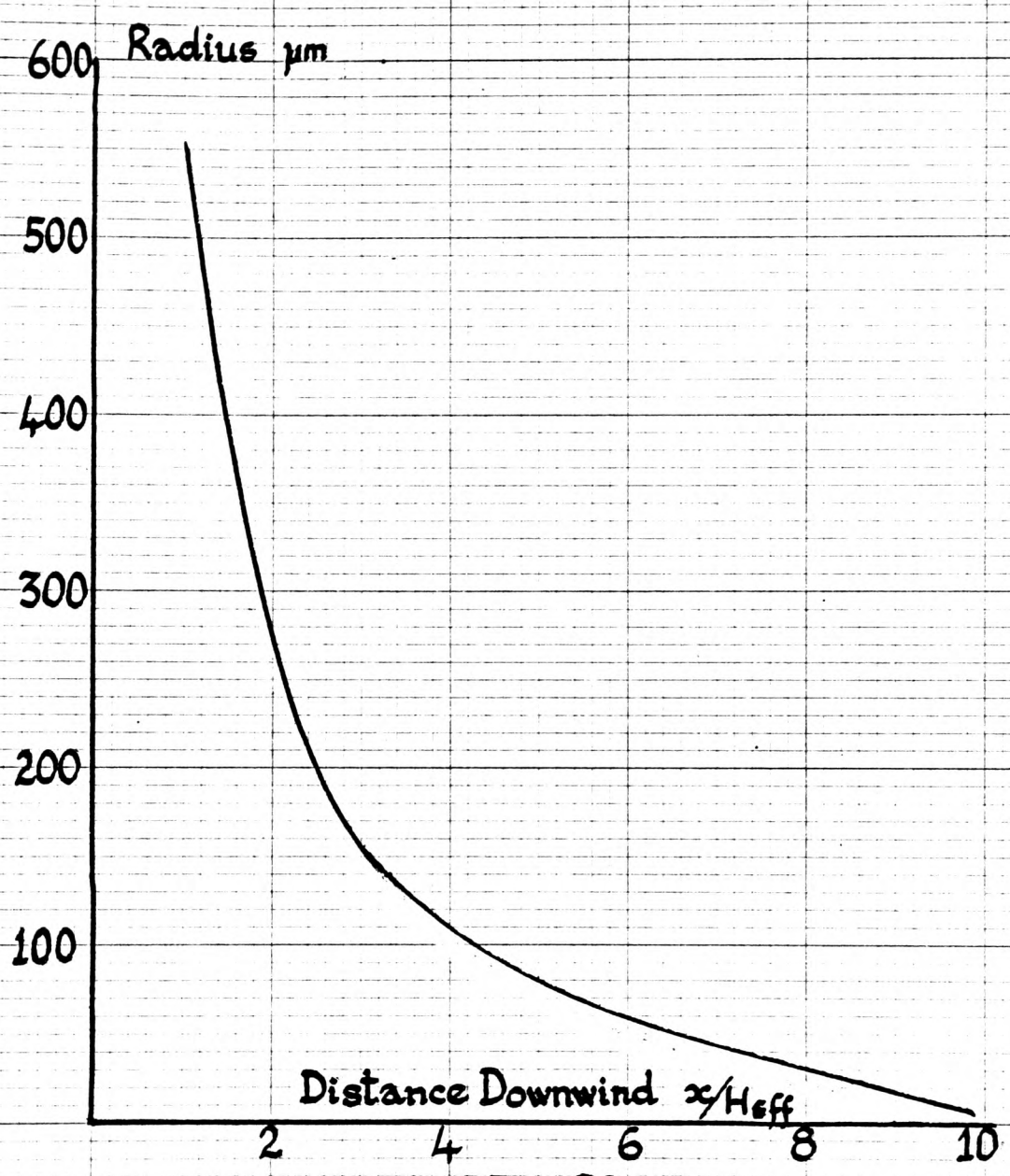


Fig. 89
Distance Downwind To Point Of Maximum Deposition
As A Function Of Particle Size
[Bosanquet, McDonald - Particle Density 1000 kg m^{-3}]

plume after a plume rise of only circa 25m according to Fig. 87 , the effective height of discharge will be circa 50m, reached quite close to the quench tower and hence they will deposit mainly within 100m. The intense local nuisance caused in such circumstances would be relieved by installation of arrestors, as shown in Chapter 3.

As the plume moves downwind, progressively smaller particles will leave it, and begin their descent from progressively greater effective heights of discharge. For a given particle size, this height can be read from Fig. 88, while for the same particle size, the distance downwind to the point of maximum deposition can be read from Fig. 89 in units of x/H . To this distance must be added the distance downwind to the point at which a particle of that size begins its fall from the plume (x_{Eff}), in order to obtain the total distance from the quench tower source to the point of maximum deposition (x_{Max}).

The results for the open tower and with arrestment are shown in Fig. 90. The major effect of enhanced dispersion is clearly found with the finer material. Particles of 50 μ m radius, which are at the lower end of the size range defined as grit(50), and still relatively coarse in air pollution terms, will be dispersed beyond 2500m from the tower with arrestment. On the basis that the effective height of discharge for the finest particles would be circa 230m at a distance of circa 900m downwind, and that $x/H = 10$ for such particles, their maximum ground level concen-

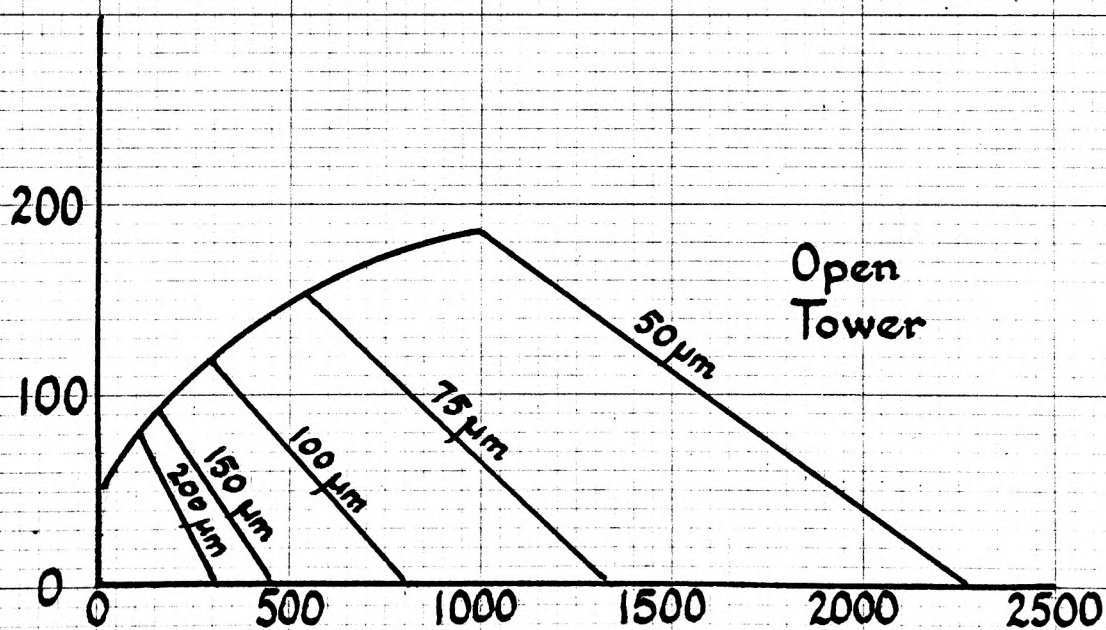
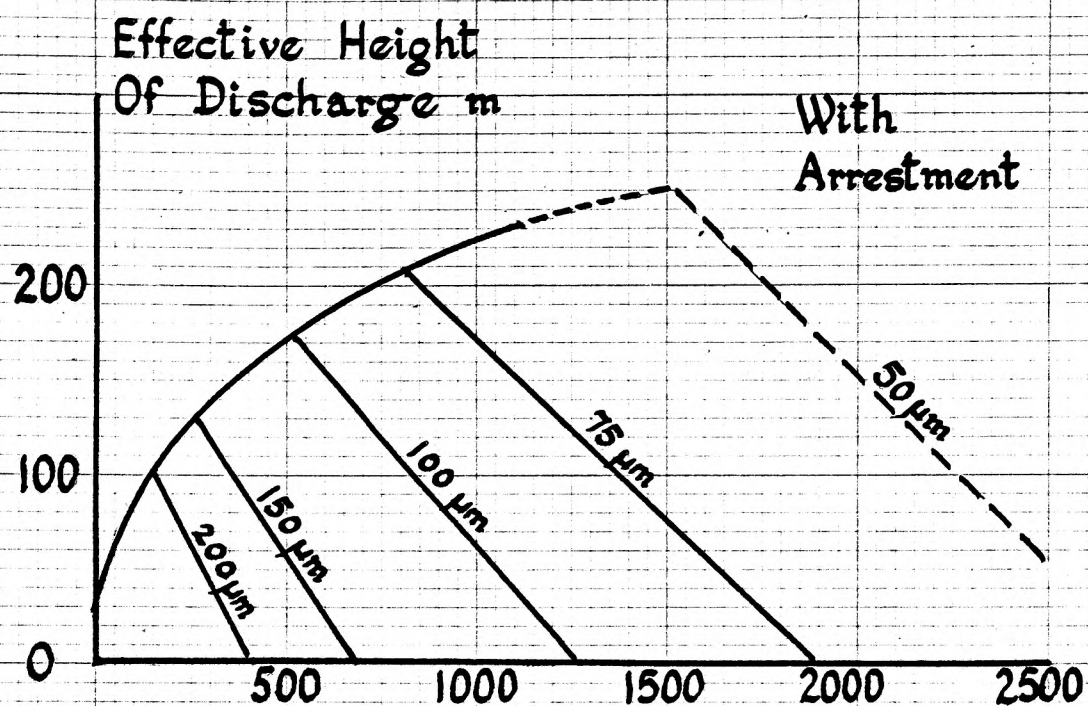


Fig.90
Distances To Points Of Maximum Deposition For
Open Tower And With Arrestment

tration will occur more than 3000m downwind. Compared to the open tower, the area over which the particles deposit will be about doubled, leading to ground level concentrations some 50% lower for the same emission. Together with the absolute emission reduction on fitting arrestors, this will lead to a major improvement in distant deposition gauges where quench emissions had been the major source.

It is probable that the value calculated for plume rise for the tower with arrestment is conservative, for two reasons. Firstly, the effect of the water gas reaction has been ignored. Secondly, the gas velocity has been based on the observations within the first few seconds after the start of the quench, whereas published work (19,26,36) indicates that peak values are higher than these initial velocities, and reached after about 20s. Nevertheless, even with these conservative values, it is shown that installation of arrestors will enhance the dispersion from quench towers.

There are consequently many effects from installation of grit arrestment:-

- (a) The effective use of the full plan area of the tower
- (b) The mechanical capture effect of the arrestors
- (c) The increase in efflux temperature
- (d) The enhancement of terminal settling velocity
- (e) The enhancement of thermal plume rise

These effects combine to produce the changes which have been observed, and proved, in the external deposit gauges.

CONCLUSIONS FOR CHAPTER 2

1. Data published as part of the National Survey indicate that deposition around iron and steel works is some of the highest in the U.K.
2. Comparison of deposition data during periods of normal activity and periods of very low activity demonstrate the marked effect of the process operations on local deposition in the absence of effective controls.
3. Based on the weight of material collected in external deposit gauges, the coke production area constitutes the most significant source of particulate emissions.
4. In the coke production area, two main emission sources have been identified, oven discharge and coke quench.
5. Following planned improvements affecting these main emission sources, evaluation of external deposition values by the conventional CuSum technique gave similar points of inflexion at most gauges, irrespective of their bearing from the coke production area.
6. The emissions from the two main sources have different spatial configurations. All gauges were affected by quench tower modifications, but only the relatively nearer gauges were affected significantly when carbonisation control was improved.

7. By improved control of the two main sources of particulate matter, the deposited material collected in external gauges can be reduced to amounts which lead to the virtual cessation of complaints due to deposition of grit and dust.
8. Operations at an iron and steel works can affect gauges more than 2500m away.
9. The conventional CuSum technique can be used to evaluate the effect of known process changes on deposit gauge results, but is limited by seasonal variations.
10. The major seasonal variation is the wind direction.
11. At any gauge, for a given level of emission, one may expect marked differences in deposited matter between the various months of the year, with a pattern that varies from gauge to gauge.
12. During any month, for a given level of emission, one may expect marked differences in deposited matter in the various gauges, since they are at different bearings from the sources.
13. The effect of the seasonal variations on evaluation of the data can be minimised by using a modification of the Cumulative Sum technique, in which the reference value is taken as the deposition value for the corres-

ponding month of the previous year.

14. If a Deposition CuSum chart is started before a works comes into operation, it can be used to estimate the incremental impact of that works on local deposition . If plotted for an existing works, using current data, it can be used to show if emissions are improving or deteriorating, and the point of onset of such changes.
15. A Deposition CuSum chart is particularly useful in monitoring the effect of known process changes, and allows more rapid evaluation of whether the changes have been beneficial or adverse.
16. A step change on a Deposition CuSum chart is a very sensitive indicator that a change in emission levels has taken place. If the chart for a gauge shows no inflexion as a result of process changes made, then emissions from the source under investigation are not reaching that gauge.
17. Inadequate grit arrestment is a major source of variance in deposition data.
18. Contamination of a deposit gauge is rendered more obvious by the use of the Deposition CuSum technique.
19. The "Span" method used to evaluate the significance of changes with the conventional CuSum technique can be

adapted for use with the Deposition CuSum technique, based on the dissection properties of CuSum charts.

20. The step change on a Deposition CuSum chart equals twice the standardised vertical distance arising on a conventional CuSum chart from the use of the "span" method of evaluation with data covering 24 months.
21. Evaluation of the reductions in deposited matter following grit arrestor modifications shows that they were significant at the 99.5% level or greater for 5 out of 7 gauges, and at the 97.5% level for the remainder.
22. Similar evaluations of the reductions following carbonisation control show that those in the nearest gauges were significant at the 99.5% level, whereas they were not significant at the other gauges.
23. The ash content of the deposited matter abated by carbonisation control is high (75-95%), indicating a high mineral matter content, and hence a relatively higher density than the coke, which would lead to deposition nearer the source.
24. The ash content of the deposited matter abated by grit arrestment modifications is relatively lower than that abated by carbonisation control, which would lead to deposition further from the source.

CONCLUSIONS FOR CHAPTER 3

1. The estimated efficiency for removal of undissolved solids by quench tower arrestment systems based on the Chilton design (for elimination of drizzle from natural draught cooling tower plumes) is below 40% for particles less than 200 μ m diameter, and over 80% (possibly as high as 100%) for the coarsest particles.
2. Emission of undissolved solids from quench towers increases with increase in carbonisation temperature. Such emissions from quenching blast furnace coke are much greater than from quenching foundry coke.
3. The variation in emission rate is dependent on the water gas reaction when the coke is quenched.
4. The water gas reaction increases the gaseous emission rate during the initial phase of each quench, and will contribute to the peak exit velocities.
5. The mineral matter associated with the fixed carbon converted in the water gas reaction can represent a substantial potential source of undissolved solids emission.
6. The amount of coke fines removed from the coke breeze settling ponds is circa one order of magnitude greater than the undissolved solids emission from open quench towers. Installation of grit arrestors will thus not

lead to a significant increase in overall recovery.

7. Parallel-sided quench towers exhibit severe channelling of the exit gases in the absence of grit arrestment. This can lead to the emission of coarse particles which will deposit close to the quench tower.
8. In parallel-sided quench towers, efflux velocities seldom exceed 6 m s^{-1} , and the emission from such towers will be subject to frequent downwash caused by high wind velocity.
9. Tapered quench towers can be designed for higher efflux velocity to avoid the frequent downwash, which will give rise to deposition in a more closely-defined band than from parallel-sided towers.
10. Quench towers can be considered as elutriators of the undissolved solids released during coke quenching.
11. An important function of grit arrestors is to make more effective use of the full plan area of quench towers, and hence to reduce peak exit velocity.
12. The experiments at B.S.C. Llanwern have shown that arrestment efficiency can be enhanced significantly by ensuring that the rising plume is presented with a continuous arrestment surface. The improved efficiency manifested itself by reductions at all the external

BS deposit gauges sited to monitor operations at that works, including some over 2.5km from the source.

13. In the case of two of the gauges, the reductions were in excess of 50%. Taking into account the background deposition from other sources, this indicates that for those gauges the quench towers were the most significant source of deposited undissolved solids.
14. Systems for monitoring deposition from coke works must consider possible interactions from other coke works within 5km distance.
15. Confirmatory experiments at other coke works based on deposit gauges sited within 200m of quench towers fitted with 70° louvres have shown that changes in the grit arrestment system cause improvements in deposition of undissolved solids which are highly significant:
 - (a) Removal of a fine coke build-up to restore the original design velocity through the louvres gave a significant reduction in deposition, and showed that a single layer of louvres based on the Chilton design does not present a continuous arrestment surface.
 - (b) Increasing the louvre section and decreasing the angle of inclination to ensure that a continuous arrestment surface is presented to the rising steam plume has led to reductions in excess of 50% in nearby gauges at other works.

16. The arrestment efficiency for undissolved solids in the steam plumes in quench towers is lower than that for the elimination of drizzle in natural draught cooling towers, based on the Chilton design. This is due to the greater upward velocity in quench towers, and the absence of a continuous arrestment surface.
17. There is a marked reduction in the variance of the deposition data for undissolved solids following installation of uprated arrestment systems. Subsequent process changes can then be monitored with greater sensitivity using the Deposition technique.
18. The changes at nearby gauges are mirrored at more distant gauges, confirming the dispersion of undissolved solids to more than 3km from the source.
19. Increased emissions of undissolved solids from quench towers due to operation at higher carbonisation temperatures can affect distant deposit gauges to an extent which is clearly detectable using the Deposition CuSum technique.
20. Arrestment systems which increase the collection efficiency for undissolved solids have been shown to increase the emission of dissolved solids, contrary to suggestions found in the literature. This leads to increases in deposition in nearby gauges which are highly significant.

21. The increased emission of dissolved solids can be abated by installation of irrigation sprays above the grit arrestors.
22. The irrigation sprays would only be required to operate during peak emission rates from the quench tower. The volume of water needed for the sprays would then be similar to the fresh water make-up to the system, and all the make-up water could be fed by this route.
23. Increased deposition of dissolved solids at distances in excess of 5km from quench towers, after uprating grit arrestment, can be detected by the Deposition CuSum technique.
24. During quenching, temporary hardness in the quench water will be converted into insoluble CaCO_3 , which may be emitted as fine particulate matter. This has the effect of softening the recirculating quench water. Permanent hardness will be unaffected by the quenching operation, and evaporation will increase the hardness of the recirculating quench water. The ratio between the hardness of the recirculating quench water and that of the make-up water will depend on the form of hardness in the make-up water.
27. To avoid excessive emission of dissolved solids from quench towers, it may be necessary to impose quality standards on the water to be used for quenching.

CONCLUSIONS FOR CHAPTER 4

1. The Shift Average Temperature is not an adequate control parameter for effective carbonisation.
2. Variations in moisture content of the coal feed can have a significant effect on heat requirements for acceptable carbonisation.
3. Variations in bulk density of the coal feed can have a significant effect on heat requirements for acceptable carbonisation.
4. When heating flues are blocked, extra heat input overall to the coke oven battery will not be practicable to prevent under-carbonisation.
5. When heating flues are in good condition, the design operating curves for coal carbonisation are satisfactory criteria to prevent Grade 3 pushing emissions.
6. Carbonisation CuSum control can maintain heating flues much closer to the requirements of the operating curves than more traditional methods.
7. Consistent timing of flue temperature measurements in relation to reversals of the regenerators, or use of cooling curves, are essential to provide meaningful values of the Carbonisation CuSum.

8. It has been shown that there is a clear relationship between the magnitude of the Carbonisation CuSum and the severity of external complaints due to deposition of grit and dust.
9. It has been shown that the application of additional heat input, as a means of reducing the Carbonisation CuSum, does not have a sufficiently rapid response time, and that reductions in the production schedule are the most practicable method.
10. The recovery of blocked heating flues can be simplified by using the Carbonisation CuSum method to indicate those flues in need of priority attention.
11. It has been shown that changing from firing with blast furnace gas to coke oven gas can lead to rapid transient increase in the Carbonisation CuSum, and that for minimum process variance, firing by blast furnace gas is preferred whenever practicable.
12. It has been shown that attempts to make up lost production by increasing the pushing schedule by one oven per shift would increase the Carbonisation CuSum by 1000°C , and lead to under-carbonisation.
13. No adverse effect on blast furnace operation has been noted using coke prepared by the Carbonisation CuSum method of control.

14. The application of Carbonisation CuSum control has led to an improvement in the grade of emission from the coke oven battery chimneys.
15. A system of data handling using a microcomputer is feasible for more rapid calculation of the Carbonisation CuSum, as an aid to decision-making.
16. A sequential method of evaluation, with data being entered in real-time rather than retrospectively, would be a more effective method of control.
17. The effect of Grade 3 discharge emissions on deposition values has been shown to be highly significant at nearby gauges, and not significant at more distant gauges.
18. The prevention of Grade 3 discharge emissions by the use of the Carbonisation CuSum will simplify the subsequent application of any items of arrestment equipment considered necessary for further abatement.
19. Used in conjunction with uprated grit arrestment, Carbonisation CuSum control has led to a virtual cessation of complaints due to deposition of grit and dust emitted from the coke plant at a major steel works.
20. Technology exists on the newer coke oven batteries for the Carbonisation CuSum calculation to be automated.

CONCLUSIONS FOR CHAPTER 5

1. The method proposed by Wagener to determine the composition of the air/water vapour mixtures in a quench tower indicates that the installation of arrestors leads to a marked reduction in the amount of air entrained by the chimney effect.
2. The work of Chocholac indicates that if the pressure drop across the arrestor is greater than the potential energy of the tower, no air will be entrained, and the gas in the tower may be heated above 373K.
3. Stokes Law will not apply to the majority of particles in a quench tower, for the calculation of terminal settling velocity. The method described by McDonald should be used instead. The terminal settling velocities are lower than those predicted by Stokes Law for particles of size relevant to this study.
4. The changes in gas temperature and gas composition which arise from the installation of arrestors act so as to increase the terminal settling velocity for a given particle.
5. By assuming that particles in a quench tower act as perfect spheres, it can be shown that reported particle size distributions of emitted solids are consistent with an effective particle density of circa 1000kg m^{-3} .

6. The installation of arrestors has a major influence on the particle size of emitted solids, irrespective of any mechanical capture effect.
7. Particles of such a size as to be bouyant in a quench tower will be accelerated upwards, and will approach asymptotically an upward velocity equal to the gas efflux velocity less the terminal settling velocity for the given particle.
8. For the majority of the emitted particles, the terminal settling velocity will be reached within 1s, but for the larger particles, the net upward velocity may not be sufficient to allow their escape from the tower in the time available during the velocity peak.
9. Due to the time required for transit of the quench tower, the maximum size elutriated in practice will be less than that predicted from the peak efflux velocity.
10. Relatively unsophisticated upper cleaning sprays should be effective in quench towers, since the largest potential targets would be virtually stationary.
11. The presence of water gas in the quench tower makes no significant difference to terminal settling velocity.

CONCLUSIONS FOR CHAPTER 6

1. An open quench tower operates at a gas flow where the available draught is balanced by the system resistance.
2. Calculations with published data show that the resistance due to condensation decreases with increasing gas temperature, and that N can be taken as unity at 373K.
3. Consideration of the equilibrium diagram for a quench tower predicts that the imposition of additional pressure drop (by installation of arrestors) will increase the absolute amount of water vapour emitted, due to the reduced condensation at higher efflux temperatures.
4. Calculations based on published data confirm this, both for parallel-sided and tapered quench towers.
5. Reduction in condensation in the tower leads to greater emissions of soluble salts, which appear as enhanced deposition of dissolved solids in surrounding gauges.
6. At B.S.C. Llanwern the installation of high pressure drop arrestors reduces the efflux velocity by 45%, while causing the water vapour emission rate to double.
7. For the open towers at B.S.C. Llanwern, the theoretical maximum particle radius elutriated is circa $1950\mu\text{m}$ at 338K, and with arrestment, circa $650\mu\text{m}$ at 373K.

CONCLUSIONS FOR CHAPTER 7

1. The change in gas composition within a quench tower on fitting arrestors is such that the emission is more bouyant.
2. As the gas temperature increases, the time taken to reach the efflux velocity, under the influence of bouyancy alone, decreases markedly. With open towers, the time exceeds 4s, but it is less than 1s for towers with arrestment.
3. The time taken to reach final plume rise exceeds 200s for emissions from open towers, but is less than 200s with arrestment.
4. Under calm conditions, the plume rise from a quench tower serving 6m ovens is in the order of 550m.
5. Wind velocity has a very significant effect on the rise of the plume. A wind velocity of 5m s^{-1} is appropriate for the Llanwern area.
6. Efflux velocity from quench towers has a modest effect on the rise of the plume, provided that it is sufficient to avoid downdraught by the wind.

7. The plume rise from an open tower serving 6m ovens is in the order of 165m. With arrestment, this increases to circa 190m, based on conservative input data. On fitting arrestors, there is a significant reduction in the plume rise component due to efflux velocity.
8. The effect of the water gas reaction is relatively modest, and leads to an increase in plume rise of circa 5%, which has been ignored in later calculations.
9. The vertical velocity of a bouyant plume decreases rapidly with distance downwind from the tower. In the case of the open tower serving 6m ovens, the efflux velocity of 7.9m s^{-1} falls to circa 3m s^{-1} within 20-30m of the tower, and will give rise to high deposition rates in the immediate vicinity of the tower. In the case of the tower with arrestment, after dissipation of the component due to efflux velocity, the vertical velocity is greater than for the open tower, at all distances downwind.
10. Particles are considered to fall from the plume when their terminal settling velocity exceeds the vertical velocity of the plume.
11. The major effect of enhanced dispersion is found with the finer particles. Based on effective heights of discharge in the order of 200m, reached 200m downwind, and maximum ground level concentration for the finest

material being found at $10.H_{\text{Eff}}$ downwind, material emitted from quench towers will be dispersed beyond 3km from the source.

12. Based on the dispersion criteria, for a source of the same magnitude, installation of arrestors would lead to a reduction of circa 50% in ground level concentration.
13. The assumptions used in calculating plume rise from the tower with arrestors have been conservative, but nevertheless, dispersion is greater than from the open tower.

APPENDIX 1

COMPUTER PROGRAM BASED ON THE McDONALD EQUATIONS FOR TERMINAL SETTLING VELOCITY

```
100 CLS
110 REMark mcdonald equations
120 DIM vv(1)
130 PRINT "input data for 'Q' calculation"
140 PRINT "\
150 PRINT FILL$("*",37)
160 INPUT "particle density (kg/m3)";pd
170 LET pd=pd/1000
180 INPUT "gas density(kg/m3)";gd
190 LET gd=gd/1000
200 INPUT "efflux velocity (m/s)";ev
210 LET ev=ev*100
220 g=981
230 INPUT "kinematic viscosity (mm2 s)";kv
240 LET kv=kv/100
250 INPUT "particle radius (0m)";pr
260 pr=pr/10000
270 w=(4/3)*PI*(pr^3)*pd*g
280 PRINT FILL$("*",37)
290 PRINT\ "particle wt. = ";w; "dynes"
300 PRINT
310 q=(8*w)/(PI*gd*kv^2)
320 PRINT "Q factor = ";q
330 PRINT
340 GO SUB 470
350 PRINT "reynolds no. = ";re
360 PRINT
370 GO SUB 650
380 PRINT "drag coefficient = ";cd
390 PRINT
400 GO SUB 820
410 PRINT\ "terminal velocity= ";tv/100;" m/sec"
420 fb=.5*gd*ev^2*cd*PI*pr^2
430 PRINT
440 PRINT "bouyancy = ";fb;" dynes"
450 PRINT
460 GO TO 250
470 REMark calculation of re
480 IF q<=24 THEN GO SUB 850:GO TO 410
490 IF q<=64 THEN re=.10583*(q^.7067): GO TO 640
500 IF q<=140 THEN re=5.031E-2*(q^.88552): GO TO 640
510 IF q<=230 THEN re=7.067E-2*(q^.81675): GO TO 640
520 IF q<=420 THEN re=5.952E-2*(q^.8483): GO TO 640
530 IF q<=1160 THEN re=.16225*(q^.68228): GO TO 640
540 IF q<=2880 THEN re=9.23E-2*(q^.76223): GO TO 640
550 IF q<=5400 THEN re=.23479*(q^.64502): GO TO 640
```

```

560 IF q<=12000 THEN re=.24592*(q^.63973): GO TO 640
570 IF q<=32000 THEN re=.131*(q^.7067): GO TO 640
580 IF q<=97600 THEN re=.31676*(q^.62158): GO TO 640
590 IF q<=194000 THEN re=.45417*(q^.59021): GO TO 640
600 IF q<=460000 THEN re=.44621*(q^.59167): GO TO 640
610 IF q<=1.64E6 THEN re=.8172*(q^.54526): GO TO 640
620 IF q<=6.4E6 THEN re=1.37169*(q^.50907): GO TO 640
630 IF q<=1.44E7 THEN re=1.58114*SQRT(q)
640 RETURN
650 REMark calculation of cd
660 IF re<=2 THEN cd=24*(re^(-.585)): GO TO 810
670 IF re<=4 THEN cd=29.09*(re^(-.8625)): GO TO 810
680 IF re<=6 THEN cd=26.14*(re^(-.7854)): GO TO 810
690 IF re<=10 THEN cd=28.04*(re^(-.8246)): GO TO 810
700 IF re<=20 THEN cd= 14.37*(re^(-.5343)): GO TO 810
710 IF re<=40 THEN cd=22.78*(re^(-.6881)): GO TO 810
720 IF re<=60 THEN cd= 9.454*(re^(-.4497)): GO TO 810
730 IF re<=100 THEN cd=8.97*(re^(-.4368)): GO TO 810
740 IF re<=200 THEN cd=17.75*(re^(-.585)): GO TO 810
750 IF re<=400 THEN cd=6.357*(re^(-.3912)): GO TO 810
760 IF re<=600 THEN cd= 3.694*(re^(-.3006)): GO TO 810
770 IF re<=1000 THEN cd= 4.022*(re^(-.3139)): GO TO 810
780 IF re<=2000 THEN cd=1.448*(re^(-.166)): GO TO 810
790 IF re<=4000 THEN cd=.5375*(re^(-3.5623E-2)): GO TO 810
800 IF re<=6000 THEN cd=.4
810 RETURN
820 REMark calc of terminal velocity
830 tv=re*kv/(2*pr)
840 RETURN
850 tv=SQRT(2*pd*g*pr^2/(9*kv*gd))
860 RETURN
870 LET t=1E-3:LET num=1
880 LET upvel=0
890 LET m=w/981
900 LET re=2*ev*pr/kv
910 GO SUB 650
920 LET by=.5*gd*ev^2*cd*PI*pr^2
930 LET nett_up=by-w
940 LET accel=nett_up/m
950 LET upvel=upvel+(accel*t)
960 LET ev=ev-(accel*t)
970 IF num=1 THEN PRINT re\cd\by\w\nett_up\accel/100:PAUSE
980 PRINT\
990 IF num >200:IF num MOD 100<>0 THEN GO TO 1030
1000 IF num MOD 20=0 THEN
1010 PRINT (num*t)\accel/100\upvel/100:PAUSE
1020 END IF
1030 num=num+1
1040 GO TO 900

```

APPENDIX 2

COMPUTER PROGRAM BASED ON THE BOSANQUET EQUATIONS FOR THE RISE OF A BOUYANT PLUME

```
100 REMark bosanquet equations
110 REMark covers both 1950 paper and 1957 paper
120 CLS
130 MODE 4
140 DIM a(20)
150 LET lapse=3E-3
160 LET grav=9.81
170 LET wind=5
180 LET delta=.13
190 INPUT "exit velocity m/s " ! ev
200 INPUT "actual gas volume m3/s " ! vol
210 INPUT "actual gas temp K " ! temp
220 INPUT "actual gas density kg/m3 " ! gd
230 PRINT FILL$("*",37)
240 equiv=gd*temp/1.22
250 PRINT "equiv ambient temp= ";equiv
260 LET diff=temp-equiv
270 PRINT "equiv temp diff= ";diff
280 LET Q=vol*equiv/temp
290 PRINT "Q at T1= ";Q
300 LET j1=(wind^2)/SQRT(Q*ev)
310 LET j2=.43*SQRT(equiv/(grav*lapse))
320 LET j3=.28*(ev*equiv)/(grav*diff)
330 LET j=j1*(j2-j3)+1
340 LET factor=LN(j^2)+2/j-2
350 PRINT "j= ";j
360 PRINT "factor= ";factor
370 PRINT FILL$("*",37)
380 LET bouyancy_pr= 6.37*Q*diff*factor*grav/(wind^3*equiv)
390 PRINT "bouyancy_pr= ";bouyancy_pr
400 LET v1=4.77*SQRT(Q*ev)
410 LET v2=wind+.43*wind^2/ev
420 LET mom_pr=v1/v2
430 PRINT "velocity_pr= ";mom_pr
440 PRINT FILL$("*",37)
450 LET X_factor=3.57*SQRT(Q*ev)/wind
460 LET Z_factor=bouyancy_pr/factor
470 PRINT "OPTIONS AVAILABLE:"\
480 PRINT "Repeat Calcs. (1)"\
490 PRINT "Plume Path Graph (2)"\
500 PRINT "Bosanquet(3)"\
510 PRINT "Rise in a Calm (4)"\
520 PRINT "Upper limit of (t+t0) (5)"\
530 PRINT "Momentum plume rise (6)"\
540 INPUT;choice
550 IF choice=1 THEN GO TO 190
```

```

560 IF choice=2 THEN GO TO 630
570 IF choice=3 THEN GO TO 860
580 IF choice=4 THEN GO TO 3400
590 IF choice=5 THEN GO TO 3500
600 IF choice=6 THEN GO TO 3540
610 PRINT FILL$("*",37)
620 REMark plume path graph
630 PRINT "X-factor= ";X_factor
640 PRINT "Z-factor= ";Z_factor
650 n=1
660 INPUT"distance downwind (m) ";dist
670 LET x=dist/X_factor
680 REMark time to travel 50m
690 LET time=50/wind
700 PRINT "x= ";x
710 LET alpha=(x+1)^2
720 LET z=LN(alpha)+2*SQRT(1/alpha)-2
730 PRINT z
740 LET path_ht=z*bouyancy_pr/factor
750 LET a(n)=path_ht:n=n+1
760 PRINT path_ht
770 IF n=11 THEN
780 PRINT FILL$("*",37)
790 PRINT "AVERAGE UPWARD VELOCITY"\
800 FOR up=1 TO 10
810 PRINT 50*up,(a(up)-a(up-1))/time
820 END FOR up
830 END IF
840 PRINT FILL$("*",37)
850 GO TO 660
860 REMark Bosanquet (2)
870 LET delta=.13
880 LET aa=9.4175*grav*Q*diff/(equiv*wind^4)
890 LET timeo=4*ev*equiv/(3*grav*diff)
900 PRINT "time_o= ";timeo
910 INPUT "distance downwind ";dist
920 LET time=dist/wind
930 xo=2.6667*PI*Q*ev*wind^4*delta^2*equiv^2/((grav*Q*diff)^2)
940 LET x=(time+timeo)/aa
950 GO SUB 1060
960 IF ev/wind>=.48 THEN
970 LET fx_2=.615*SQRT(xo)/SQRT((ev^2/wind^2)+.57)
980 END IF
990 IF ev/wind<.48 THEN
1000 LET fx_2=(1.311-.9*SQRT(ev/wind))*SQRT(xo)
1010 END IF
1020 PRINT "Correction= ";fx_2,fx_2*aa*wind\
1030 LET plumerise=aa*wind*(fx+fxo-fx_2)
1040 PRINT "Plumerise = ";plumerise\
1050 GO TO 910
1060 REMark interpolation of bosanquet
1070 IF x<=1.2E-3 THEN fx=1.054*x^.75
1080 IF x<=1.4E-3 THEN fx=.918974*x^.731722:GO TO 2200

```

```

1090 IF x<=1.6E-3 THEN fx=1.0995*x^.759016:GO TO 2200
1100 IF x<=1.8E-3 THEN fx=1.26876*x^.781258:GO TO 2200
1110 IF x<=2E-3 THEN fx=.775559*x^.703375:GO TO 2200
1120 IF x<=2.5E-3 THEN fx=1.07338*x^.755669:GO TO 2200
1130 IF x<=3E-3 THEN fx=1.03814*x^.750098:GO TO 2200
1140 IF x<=3.5E-3 THEN fx=.961654*x^.736923:GO TO 2200
1150 IF x<=4E-3 THEN fx=.865696*x^.718334:GO TO 2200
1160 IF x<=4.5E-3 THEN fx=.99231*x^.743056:GO TO 2200
1170 IF x<=5E-3 THEN fx=1.1099*x^.763781:GO TO 2200
1180 IF x<=6E-3 THEN fx=.975704*x^.739459:GO TO 2200
1190 IF x<=7E-3 THEN fx=1.00154*x^.744567:GO TO 2200
1200 IF x<=8E-3 THEN fx=.871337*x^.71645:GO TO 2200
1210 IF x<=9E-3 THEN fx=.982294*x^.741325:GO TO 2200
1220 IF x<=1E-2 THEN fx=.943655*x^.732805:GO TO 2200
1230 IF x<=1.2E-2 THEN fx=.998698*x^.745116:GO TO 2200
1240 IF x<= 1.4E-2 THEN fx=.929647*x^.728916:GO TO 2200
1250 IF x<=1.6E-2 THEN fx=.908889*x^.723626:GO TO 2200
1260 IF x<=1.8E-2 THEN fx=.936957*x^.730982:GO TO 2200
1270 IF x<=2E-2 THEN fx=.951049*x^.734697:GO TO 2200
1280 IF x<=2.5E-2 THEN fx=.933675*x^.729984:GO TO 2200
1290 IF x<=3E-2 THEN fx=.908662*x^.722623:GO TO 2200
1300 IF x<=3.5E-2 THEN fx=.909733*x^.722959:GO TO 2200
1310 IF x<=4E-2 THEN fx=.892171*x^.717144:GO TO 2200
1320 IF x<=4.5E-2 THEN fx=.887689*x^.715579:GO TO 2200
1330 IF x<=5E-2 THEN fx=.873539*x^.710398:GO TO 2200
1340 IF x<=6E-2 THEN fx=.95164*x^.738983:GO TO 2200
1350 IF x<=7E-2 THEN fx=.789471*x^.672579:GO TO 2200
1360 IF x<=8E-2 THEN fx=.857003*x^.703444:GO TO 2200
1370 IF x<=9E-2 THEN fx=.914096*x^.728978:GO TO 2200
1380 IF x<=.1 THEN fx=.841858*x^.69479:GO TO 2200
1390 IF x<=.12 THEN fx=.844164*x^.695978:GO TO 2200
1400 IF x<=.14 THEN fx=.85189*x^.700275:GO TO 2200
1410 IF x<=.16 THEN fx=.796557*x^.666117:GO TO 2200
1420 IF x<=.18 THEN fx=.837491*x^.693462:GO TO 2200
1430 IF x<=.2 THEN fx=.821307*x^.682083:GO TO 2200
1440 IF x<=.25 THEN fx=.820483*x^.681458:GO TO 2200
1450 IF x<=.3 THEN fx=.799959*x^.663185:GO TO 2200
1460 IF x<=.35 THEN fx=.788284*x^.650973:GO TO 2200
1470 IF x<=.4 THEN fx=.786224*x^.648481:GO TO 2200
1480 IF x<=.45 THEN fx=.793463*x^.658484:GO TO 2200
1490 IF x<=.5 THEN fx=.773426*x^.626452:GO TO 2200
1500 IF x<=.6 THEN fx=.775428*x^.630182:GO TO 2200
1510 IF x<=.7 THEN fx=.774043*x^.626682:GO TO 2200
1520 IF x<=.8 THEN fx=.767828*x^.604082:GO TO 2200
1530 IF x<=.9 THEN fx=.766856*x^.598406:GO TO 2200
1540 IF x<=1 THEN fx=.767*x^.600183:GO TO 2200
1550 IF x<=1.2 THEN fx=.767*x^.576453:GO TO 2200
1560 IF x<=1.4 THEN fx=.768146*x^.568263:GO TO 2200
1570 IF x<=1.6 THEN fx=.77458*x^.543473:GO TO 2200
1580 IF x<=1.8 THEN fx=.76339*x^.574435:GO TO 2200
1590 IF x<=2 THEN fx=.789216*x^.517831:GO TO 2200
1600 IF x<=2.5 THEN fx=.786161*x^.523427:GO TO 2200
1610 IF x<=3 THEN fx=.806754*x^.495207:GO TO 2200
1620 IF x<=3.5 THEN fx=.807761*x^.494071:GO TO 2200
1630 IF x<=4 THEN fx=.868315*x^.436369:GO TO 2200
1640 IF x<=4.5 THEN fx=.831675*x^.467468:GO TO 2200

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1650 IF x<=5 THEN fx=.864759*x^.441532:GO TO 2200
1660 IF x<=6 THEN fx=.895528*x^.419808:GO TO 2200
1670 IF x<=7 THEN fx=.880376*x^.429333:GO TO 2200
1680 IF x<=8 THEN fx=.940856*x^.395188:GO TO 2200
1690 IF x<=9 THEN fx=.955528*x^.387747:GO TO 2200
1700 IF x<=10 THEN fx=.985086*x^.373882:GO TO 2200
1710 IF x<=12 THEN fx=1.007129*x^.364271:GO TO 2200
1720 IF x<=14 THEN fx=.96979*x^.379474:GO TO 2200
1730 IF x<=16 THEN fx=1.178203*x^.305711:GO TO 2200
1740 IF x<=18 THEN fx=1.092374*x^.332991:GO TO 2200
1750 IF x<=20 THEN fx=1.222435*x^.294072:GO TO 2200
1760 IF x<=25 THEN fx=1.17187*x^.308173:GO TO 2200
1770 IF x<=30 THEN fx=1.252884*x^.287406:GO TO 2200
1780 IF x<=35 THEN fx=1.259642*x^.285824:GO TO 2200
1790 IF x<=40 THEN fx=1.31066*x^.274658:GO TO 2200
1800 IF x<=45 THEN fx=1.410059*x^.254841:GO TO 2200
1810 IF x<=50 THEN fx=1.42663*x^.251771:GO TO 2200
1820 IF x<=60 THEN fx=1.422333*x^.252543:GO TO 2200
1830 IF x<=70 THEN fx=1.504545*x^.238818:GO TO 2200
1840 IF x<=80 THEN fx=1.55411*x^.230992:GO TO 2200
1850 IF x<=90 THEN fx=1.5299*x^.234767:GO TO 2200
1860 IF x<=100 THEN fx=1.685089*x^.213295:GO TO 2200
1870 IF x<=120 THEN fx=4.5+9E-3*(x-100):GO TO 2200
1880 IF x<=140 THEN fx=4.68+7.5E-3*(x-120):GO TO 2200
1890 IF x<=160 THEN fx=4.83+7E-3*(x-140):GO TO 2200
1900 IF x<=180 THEN fx=4.97+5.5E-3*(x-160):GO TO 2200
1910 IF x<=200 THEN fx=5.08+5.5E-3*(x-180):GO TO 2200
1920 IF x<=250 THEN fx=5.19+4.4E-3*(x-200):GO TO 2200
1930 IF x<=300 THEN fx=5.41+3.6E-3*(x-250):GO TO 2200
1940 IF x<=350 THEN fx=5.59+3E-3*(x-300):GO TO 2200
1950 IF x<=400 THEN fx=5.74+2.8E-3*(x-350):GO TO 2200
1960 IF x<=450 THEN fx=5.88+2.2E-3*(x-400):GO TO 2200
1970 IF x<=500 THEN fx=5.99+2.2E-2*(x-450):GO TO 2200
1980 IF x<=600 THEN fx=6.1+1.8E-3*(x-500):GO TO 2200
1990 IF x<=700 THEN fx=6.28+1.5E-3*(x-600):GO TO 2200
2000 IF x<=800 THEN fx=6.43+1.4E-3*(x-700):GO TO 2200
2010 IF x<=900 THEN fx=6.57+1.2E-3*(x-800):GO TO 2200
2020 IF x<=1000 THEN fx=6.69+1E-3*(x-900):GO TO 2200
2030 IF x<=1200 THEN fx=6.7+9E-4*(x-1000):GO TO 2200
2040 IF x<=1400 THEN fx=6.97+8E-4*(x-1200):GO TO 2200
2050 IF x<=1600 THEN fx=7.13+6.5E-4*(x-1400):GO TO 2200
2060 IF x<=1800 THEN fx=7.26+6E-4*(x-1600):GO TO 2200
2070 IF x<=2000 THEN fx=7.38+5E-4*(x-1800):GO TO 2200
2080 IF x<=2500 THEN fx=7.48+4.6E-4*(x-2000):GO TO 2200
2090 IF x<=3000 THEN fx=7.71+3.6E-4*(x-2500):GO TO 2200
2100 IF x<=3500 THEN fx=7.89+3E-4*(x-3000):GO TO 2200
2110 IF x<=4000 THEN fx=8.04+2.8E-4*(x-3500):GO TO 2200
2120 IF x<=4500 THEN fx=8.18+2.2E-4*(x-4000):GO TO 2200
2130 IF x<=5000 THEN fx=8.29+2.2E-4*(x-4500):GO TO 2200
2140 IF x<=6000 THEN fx=8.4+1.8E-4*(x-5000):GO TO 2200
2150 IF x<=7000 THEN fx=8.58+1.6E-4*(x-6000):GO TO 2200
2160 IF x<=8000 THEN fx=8.74+1.3E-4*(x-7000):GO TO 2200
2170 IF x<=9000 THEN fx=8.87+1.2E-4*(x-8000):GO TO 2200
2180 IF x<=10000 THEN fx=8.99+1E-4*(x-9000):GO TO 2200
2190 IF x>10000 THEN fx=LN(x)-.12
2200 IF xo<=1E-3 THEN fxo=-.527*xo^.75:GO TO 3340

```

```

2210 IF  $x_0 \leq 1.2E-3$  THEN  $f_{x_0} = -2.8E-3 - 2*(x_0 - 1E-3)$ :GO TO 3340
2220 IF  $x_0 \leq 1.4E-3$  THEN  $f_{x_0} = -3.2E-3 - 2*(x_0 - 1.2E-3)$ :GO TO 3340
2230 IF  $x_0 \leq 1.6E-3$  THEN  $f_{x_0} = -3.6E-3 - 1.5*(x_0 - 1.4E-3)$ :GO TO 3340
2240 IF  $x_0 \leq 1.8E-3$  THEN  $f_{x_0} = -3.9E-3 - 2*(x_0 - 1.6E-3)$ :GO TO 3340
2250 IF  $x_0 \leq 2E-3$  THEN  $f_{x_0} = -4.3E-3 - 1.5*(x_0 - 1.8E-3)$ :GO TO 3340
2260 IF  $x_0 \leq 2.5E-3$  THEN  $f_{x_0} = -4.6E-3 - 1.6*(x_0 - 2E-3)$ :GO TO 3340
2270 IF  $x_0 \leq 3E-3$  THEN  $f_{x_0} = -5.4E-3 - 1.4*(x_0 - 2.5E-3)$ :GO TO 3340
2280 IF  $x_0 \leq 3.5E-3$  THEN  $f_{x_0} = -6.1E-3 - 1.4*(x_0 - 3E-3)$ :GO TO 3340
2290 IF  $x_0 \leq 4E-3$  THEN  $f_{x_0} = -6.8E-3 - 1.4*(x_0 - 3.5E-3)$ :GO TO 3340
2300 IF  $x_0 \leq 4.5E-3$  THEN  $f_{x_0} = -7.5E-3 - 1.2*(x_0 - 4E-3)$ :GO TO 3340
2310 IF  $x_0 \leq 5E-3$  THEN  $f_{x_0} = -8.1E-3 - 1.2*(x_0 - 4.5E-3)$ :GO TO 3340
2320 IF  $x_0 \leq 6E-3$  THEN  $f_{x_0} = -8.7E-3 - 1.2*(x_0 - 5E-3)$ :GO TO 3340
2330 IF  $x_0 \leq 7E-3$  THEN  $f_{x_0} = -9.9E-3 - 1.1*(x_0 - 6E-3)$ :GO TO 3340
2340 IF  $x_0 \leq 8E-3$  THEN  $f_{x_0} = -1.1E-2 - (x_0 - 8E-3)$ :GO TO 3340
2350 IF  $x_0 \leq 9E-3$  THEN  $f_{x_0} = -1.2E-2 - .9*(x_0 - 8E-3)$ :GO TO 3340
2360 IF  $x_0 \leq 1E-2$  THEN  $f_{x_0} = -1.29E-2 - .9*(x_0 - 9E-3)$ :GO TO 3340
2370 IF  $x_0 \leq 1.2E-2$  THEN  $f_{x_0} = -1.38E-2 - .9*(x_0 - 1E-2)$ :GO TO 3340
2380 IF  $x_0 \leq 1.4E-2$  THEN  $f_{x_0} = -1.56E-2 - .8*(x_0 - 1.2E-2)$ :GO TO 3340
2390 IF  $x_0 \leq 1.6E-2$  THEN  $f_{x_0} = -1.72E-2 - .7*(x_0 - 1.4E-2)$ :GO TO 3340
2400 IF  $x_0 \leq 1.8E-2$  THEN  $f_{x_0} = -1.86E-2 - .7*(x_0 - 1.6E-2)$ :GO TO 3340
2410 IF  $x_0 \leq 2E-2$  THEN  $f_{x_0} = -2E-2 - .65*(x_0 - 1.8E-2)$ :GO TO 3340
2420 IF  $x_0 \leq 2.5E-2$  THEN  $f_{x_0} = -2.13E-2 - .58*(x_0 - 2E-2)$ :GO TO 3340
2430 IF  $x_0 \leq 3E-2$  THEN  $f_{x_0} = -2.42E-2 - .52*(x_0 - 2.5E-2)$ :GO TO 3340
2440 IF  $x_0 \leq 3.5E-2$  THEN  $f_{x_0} = -2.68E-2 - .46*(x_0 - 3E-2)$ :GO TO 3340
2450 IF  $x_0 \leq 4E-2$  THEN  $f_{x_0} = -2.91E-2 - .42*(x_0 - 3.5E-2)$ :GO TO 3340
2460 IF  $x_0 \leq 4.5E-2$  THEN  $f_{x_0} = -3.12E-2 - .38*(x_0 - 4E-2)$ :GO TO 3340
2470 IF  $x_0 \leq 5E-2$  THEN  $f_{x_0} = -3.31E-2 - .32*(x_0 - 4.5E-2)$ :GO TO 3340
2480 IF  $x_0 \leq 6E-2$  THEN  $f_{x_0} = -3.47E-2 - .28*(x_0 - 5E-2)$ :GO TO 3340
2490 IF  $x_0 \leq 7E-2$  THEN  $f_{x_0} = -3.75E-2 - .25*(x_0 - 6E-2)$ :GO TO 3340
2500 IF  $x_0 \leq 8E-2$  THEN  $f_{x_0} = -4E-2 - .2*(x_0 - 7E-2)$ :GO TO 3340
2510 IF  $x_0 \leq 9E-2$  THEN  $f_{x_0} = -4.2E-2 - .1*(x_0 - 8E-2)$ :GO TO 3340
2520 IF  $x_0 \leq .1$  THEN  $f_{x_0} = -4.3E-2 - .1*(x_0 - 9E-2)$ :GO TO 3340
2530 IF  $x_0 \leq .12$  THEN  $f_{x_0} = -4.4E-2 - .5E-2*(x_0 - .1)$ :GO TO 3340
2540 IF  $x_0 \leq .14$  THEN  $f_{x_0} = -4.5E-2 - .5E-2*(x_0 - .12)$ :GO TO 3340
2550 IF  $x_0 \leq .16$  THEN  $f_{x_0} = -4.6E-2$ :GO TO 3340
2560 IF  $x_0 \leq .18$  THEN  $f_{x_0} = -4.6E-2 + .5E-2*(x_0 - .16)$ :GO TO 3340
2570 IF  $x_0 \leq .2$  THEN  $f_{x_0} = -4.5E-2 + .1*(x_0 - .18)$ :GO TO 3340
2580 IF  $x_0 \leq .25$  THEN  $f_{x_0} = -4.3E-2 + .12*(x_0 - .2)$ :GO TO 3340
2590 IF  $x_0 \leq .3$  THEN  $f_{x_0} = -3.7E-2 + .14*(x_0 - .25)$ :GO TO 3340
2600 IF  $x_0 \leq .35$  THEN  $f_{x_0} = -3E-2 + .2*(x_0 - .3)$ :GO TO 3340
2610 IF  $x_0 \leq .4$  THEN  $f_{x_0} = -2E-2 + .2*(x_0 - .35)$ :GO TO 3340
2620 IF  $x_0 \leq .45$  THEN  $f_{x_0} = -1E-2 + .2*(x_0 - .4)$ :GO TO 3340
2630 IF  $x_0 \leq .5$  THEN  $f_{x_0} = 2E-3 + .24*(x_0 - .45)$ :GO TO 3340
2640 IF  $x_0 \leq .6$  THEN  $f_{x_0} = 1.4E-2 + .27*(x_0 - .5)$ :GO TO 3340
2650 IF  $x_0 \leq .7$  THEN  $f_{x_0} = 4.1E-2 + .27*(x_0 - .6)$ :GO TO 3340
2660 IF  $x_0 \leq .8$  THEN  $f_{x_0} = 6.8E-2 + .28*(x_0 - .7)$ :GO TO 3340
2670 IF  $x_0 \leq .9$  THEN  $f_{x_0} = 9.6E-2 + .29*(x_0 - .8)$ :GO TO 3340
2680 IF  $x_0 \leq 1$  THEN  $f_{x_0} = .125 + .3*(x_0 - .9)$ :GO TO 3340
2690 IF  $x_0 \leq 1.2$  THEN  $f_{x_0} = .155 + .285*(x_0 - 1)$ :GO TO 3340
2700 IF  $x_0 \leq 1.4$  THEN  $f_{x_0} = .212 + .285*(x_0 - 1.2)$ :GO TO 3340
2710 IF  $x_0 \leq 1.6$  THEN  $f_{x_0} = .269 + .28*(x_0 - 1.4)$ :GO TO 3340
2720 IF  $x_0 \leq 1.8$  THEN  $f_{x_0} = .325 + .275*(x_0 - 1.6)$ :GO TO 3340
2730 IF  $x_0 \leq 2$  THEN  $f_{x_0} = .38 + .25*(x_0 - 1.8)$ :GO TO 3340
2740 IF  $x_0 \leq 2.5$  THEN  $f_{x_0} = .43 + .22*(x_0 - 2)$ :GO TO 3340
2750 IF  $x_0 \leq 3$  THEN  $f_{x_0} = .56 + .26*(x_0 - 2.5)$ :GO TO 3340
2760 IF  $x_0 \leq 3.5$  THEN  $f_{x_0} = .69 + .22*(x_0 - 3)$ :GO TO 3340

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2770 IF xo<=4 THEN fxo=.8+.22*(xo-3.5):GO TO 3340
2780 IF xo<=4.5 THEN fxo=.91+.22*(xo-4):GO TO 3340
2790 IF xo<=5 THEN fxo=1.02+.22*(xo-4.5):GO TO 3340
2800 IF xo<=6 THEN fxo=1.12+.2*(xo-5):GO TO 3340
2810 IF xo<=7 THEN fxo=1.32+.18*(xo-6):GO TO 3340
2820 IF xo<=8 THEN fxo=1.5+.17*(xo-7):GO TO 3340
2830 IF xo<=9 THEN fxo=1.67+.17*(xo-8):GO TO 3340
2840 IF xo<=10 THEN fxo=1.84+.15*(xo-9):GO TO 3340
2850 IF xo<=12 THEN fxo=1.99+.145*(xo-10):GO TO 3340
2860 IF xo<=14 THEN fxo=2.28+.15*(xo-12):GO TO 3340
2870 IF xo<=16 THEN fxo=2.58+.15*(xo-14):GO TO 3340
2880 IF xo<=18 THEN fxo=2.88+.135*(xo-16):GO TO 3340
2890 IF xo<=20 THEN fxo=3.15+.13*(xo-18):GO TO 3340
2900 IF xo<=25 THEN fxo=3.41+.12*(xo-20):GO TO 3340
2910 IF xo<=30 THEN fxo=4.01+.11*(xo-25):GO TO 3340
2920 IF xo<=35 THEN fxo=4.56+.102*(xo-30):GO TO 3340
2930 IF xo<=40 THEN fxo=5.07+9.4E-2*(xo-35):GO TO 3340
2940 IF xo<=45 THEN fxo=5.54+9.2E-2*(xo-40):GO TO 3340
2950 IF xo<=50 THEN fxo=6+8.6E-2*(xo-45):GO TO 3340
2960 IF xo<=60 THEN fxo=6.43+8.1E-2*(xo-50):GO TO 3340
2970 IF xo<=70 THEN fxo=7.24+7.4E-2*(xo-60):GO TO 3340
2980 IF xo<=80 THEN fxo=7.98+7E-2*(xo-70):GO TO 3340
2990 IF xo<=90 THEN fxo=8.68+6.5E-2*(xo-80):GO TO 3340
3000 IF xo<=100 THEN fxo=9.33+6.2E-2*(xo-90):GO TO 3340
3010 IF xo<=120 THEN fxo=9.95+5.75E-2*(xo-100):GO TO 3340
3020 IF xo<=140 THEN fxo=11.1+5.5E-2*(xo-120):GO TO 3340
3030 IF xo<=160 THEN fxo=12.2+5E-2*(xo-140):GO TO 3340
3040 IF xo<=180 THEN fxo=13.2+4.5E-2*(xo-160):GO TO 3340
3050 IF xo<=200 THEN fxo=14.1+4.5E-2*(xo-180):GO TO 3340
3060 IF xo<=250 THEN fxo=15+4.2E-2*(xo-200):GO TO 3340
3070 IF xo<=300 THEN fxo=17.1+3.8E-2*(xo-250):GO TO 3340
3080 IF xo<=350 THEN fxo=19+3.4E-2*(xo-300):GO TO 3340
3090 IF xo<=400 THEN fxo=20.7+3.2E-2*(xo-350):GO TO 3340
3100 IF xo<=450 THEN fxo=22.3+3.2E-2*(xo-400):GO TO 3340
3110 IF xo<=500 THEN fxo=23.9+2.8E-2*(xo-450):GO TO 3340
3120 IF xo<=600 THEN fxo=25.3+2.7E-2*(xo-500):GO TO 3340
3130 IF xo<=700 THEN fxo=28+2.5E-2*(xo-600):GO TO 3340
3140 IF xo<=800 THEN fxo=30.5+2.3E-2*(xo-700):GO TO 3340
3150 IF xo<=900 THEN fxo=32.8+2.2E-2*(xo-800):GO TO 3340
3160 IF xo<=1000 THEN fxo=35+2E-2*(xo-900):GO TO 3340
3170 IF xo<=1200 THEN fxo=37+1.95E-2*(xo-1000):GO TO 3340
3180 IF xo<=1400 THEN fxo=40.9+1.8E-2*(xo-1200):GO TO 3340
3190 IF xo<=1600 THEN fxo=44.5+1.65E-2*(xo-1400):GO TO 3340
3200 IF xo<=1800 THEN fxo=47.8+1.55E-2*(xo-1600):GO TO 3340
3210 IF xo<=2000 THEN fxo=50.9+1.45E-2*(xo-1800):GO TO 3340
3220 IF xo<=2500 THEN fxo=53.8+1.36E-2*(xo-2000):GO TO 3340
3230 IF xo<=3000 THEN fxo=60.6+1.22E-3*(xo-2500):GO TO 3340
3240 IF xo<=3500 THEN fxo=66.8+1.12E-2*(xo-3000):GO TO 3340
3250 IF xo<=4000 THEN fxo=72.4+1.06E-2*(xo-3500):GO TO 3340
3260 IF xo<=4500 THEN fxo=77.7+9.8E-3*(xo-4000):GO TO 3340
3270 IF xo<=5000 THEN fxo=82.6+9.6E-3*(xo-4500):GO TO 3340
3280 IF xo<=6000 THEN fxo=87.4+8.7E-3*(xo-5000):GO TO 3340
3290 IF xo<=7000 THEN fxo=96.1+8E-3*(xo-6000):GO TO 3340
3300 IF xo<=8000 THEN fxo=104.1+7.5E-3*(xo-7000):GO TO 3340
3310 IF xo<=9000 THEN fxo=111.6+7E-3*(xo-8000):GO TO 3340
3320 IF xo<=10000 THEN fxo=118.6+6.7E-3*(xo-9000):GO TO 3340

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3330 IF xo>10000 THEN fxo=1.311*SQRT(xo)-LN(xo)/2-1
3340 PRINT "A= ";aa
3350 PRINT "x1= ";x\
3360 PRINT "xo= ";xo\
3370 PRINT "fx= ";fx,fx*aa*wind\
3380 PRINT "fxo= ";fxo,fxo*aa*wind\
3390 RETURN
3400 REMark rise in a calm
3410 LET term_1=.666/SQRT(delta)
3420 LET term_2=(grav*Q*diff/equiv)^.25
3430 LET term_3=(time+timeo)^.75-.5*timeo^.75
3440 LET term_4=.283*SQRT(Q/ev)/delta
3450 LET h_calm=term_1*term_2*term_3-term_4
3460 PRINT "h_calm= ";h_calm
3470 LET u_max=.53*((grav*diff)/(equiv*delta))^.4*Q^.2
3480 PRINT "u_max= ";u_max
3490 GO TO 470
3500 REMark upper limit of (t+t0)
3510 LET upper_limit=1.571*SQRT((2*equiv)/(grav*lapse))
3520 PRINT "upper limit of (t+t0)= ";upper_limit
3530 GO TO 470
3540 LET h_1=(SQRT(2*Q*ev/3))/(delta*PI^.5*wind)
3550 LET h_2=.615/SQRT((ev^2/wind^2)+.57)
3560 LET h_mom=h_1*(1.311-h_2)
3570 PRINT "mom plume rise= ";h_mom
3580 GO TO 470

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